Approach to Microwave Filters Dimensioning

Giuseppe Macchiarella
Polytechnic of Milan, Italy
Electronic and Information Department

Narrow-band Microwave Filters Design: The Basic Steps

- Definition of requirements
- Selection of technology
- Electrical design (coupling parameters evaluation)
- A priori assignments (size and type of cavities, coupling structures, tuning elements, etc)
- Definition of the geometrical unknowns

- Initial dimensioning (approximated)
- Refinement of the design
- Fabrication of a prototype
- Diagnosis and possible corrections
- Production and Tuning

Coupling Parameters

- Resonance frequencies (f_i)
- Coupling Coefficients ($k_{i,j}$)
- External Q ($Q_{S,k}$, $Q_{L,k}$)

Parallel model

$$k_{i,j} = \frac{J_{i,j}}{\sqrt{B_{eq,i} \cdot B_{eq,i}}}$$

$$Q_{S,i} = \frac{B_{eq,i}}{J_{S,i}^2} G_0, \quad Q_{L,i} = \frac{B_{eq,i}}{J_{L,i}^2} G_0$$

$$B_{eq,i} = \frac{1}{2} \omega_o \left. \frac{\partial B_{ris,i}}{\partial \omega} \right|_{\omega=\omega_o}$$

Series model

$$k_{i,j} = \frac{K_{i,j}}{\sqrt{X_{eq,i} \cdot X_{eq,i}}}$$

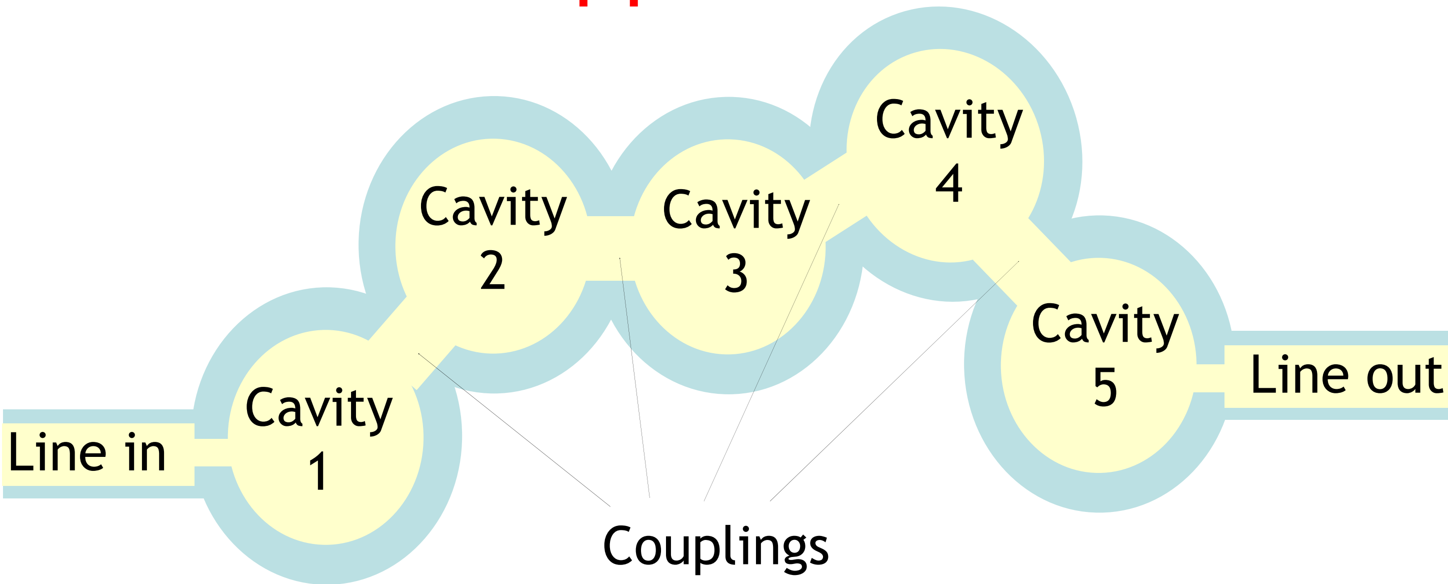
$$Q_{S,i} = \frac{X_{eq,i}}{K_{S,i}^2} R_0, \quad Q_{L,i} = \frac{X_{eq,i}}{K_{L,i}^2} R_0$$

$$X_{eq,i} = \frac{1}{2} \omega_o \left. \frac{\partial X_{ris,i}}{\partial \omega} \right|_{\omega=\omega_o}$$

Initial dimensioning

- The initial dimensioning relates the coupling parameters to the physical structure in order to derive a first order estimation of the dimensional variables of the implementing structure
- Generally this step does not resort to intensive computations and is affected by an intrinsic approximation due to the assumed equivalence between equivalent circuit and real structure

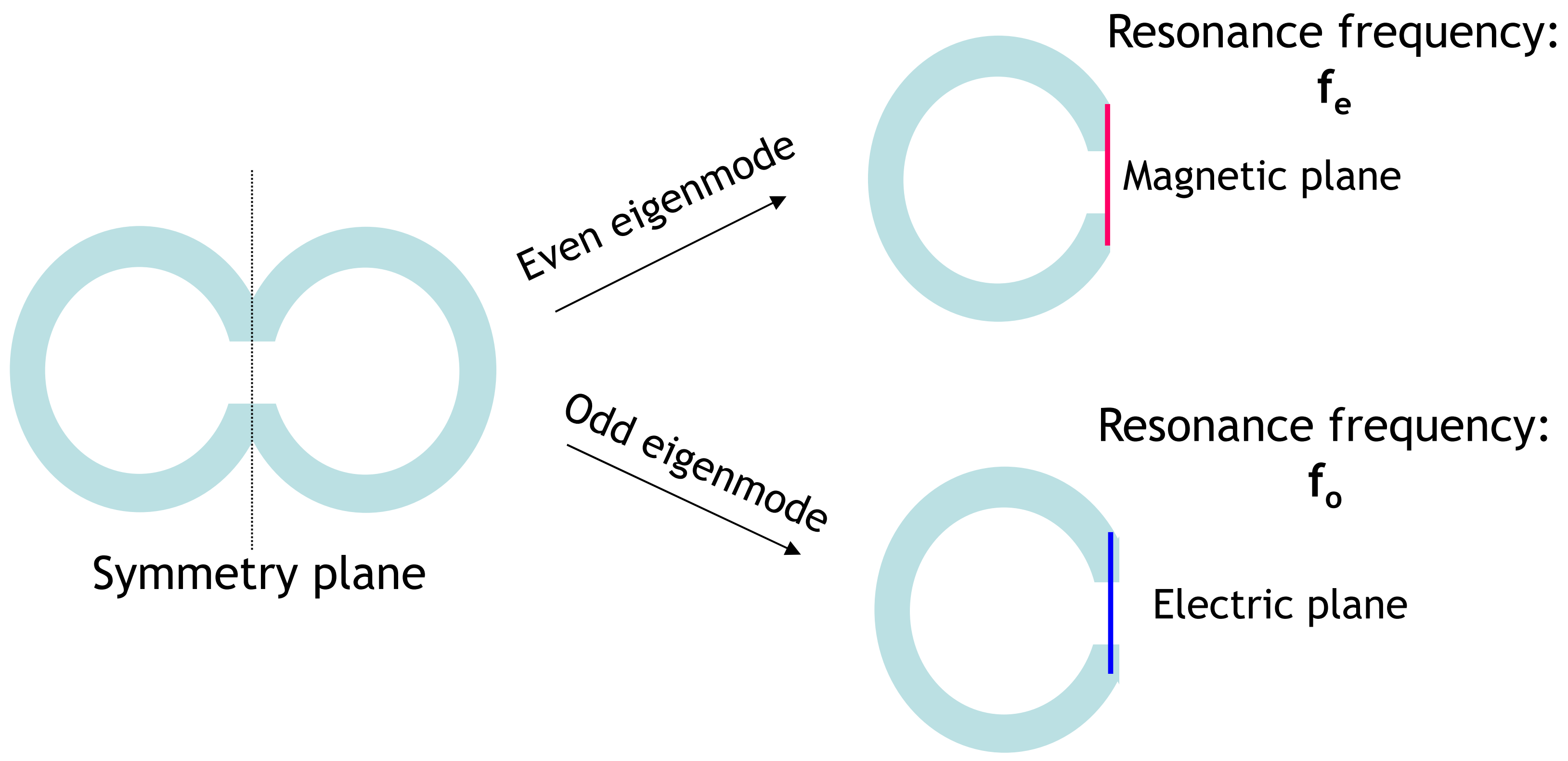
Initial dimensioning: the classical approach



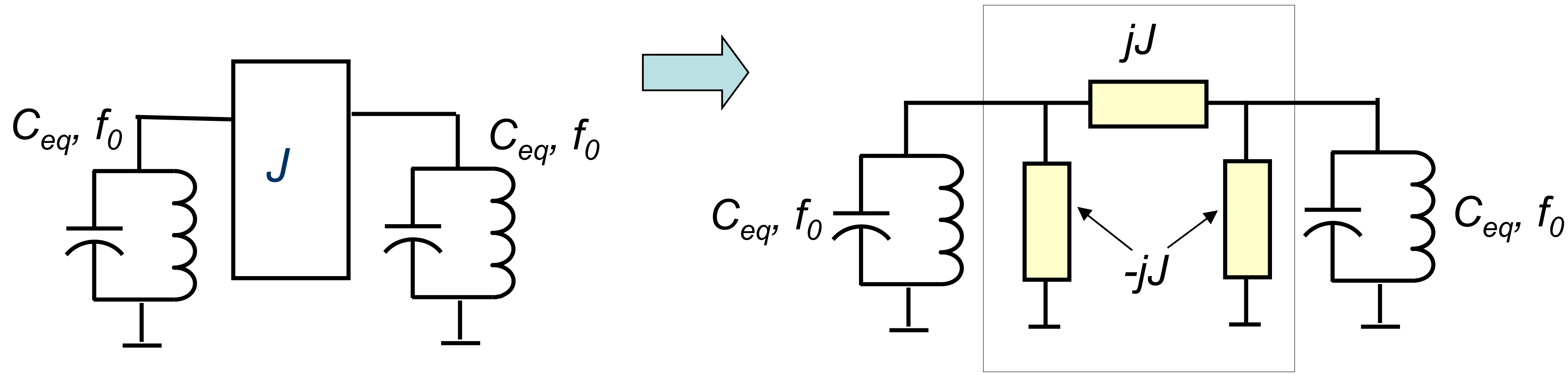
- Cavities may not be representable as terminated transmission lines
- Couplings could be physically not distinguishable from the cavities
- It is not required to identify equivalent resonators and inverters separately

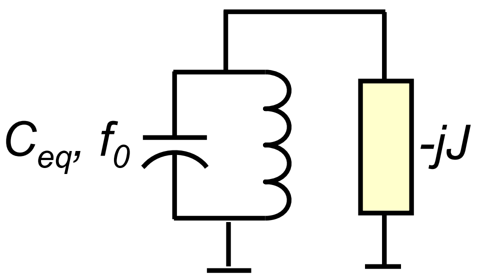
General modeling based on eigenmodes of coupled cavities

- <u>Approximation</u>:
- The couplings are considered separately (one at a time)
- The two cavities are assumed equal



Evaluation of Eigenmodes frequencies

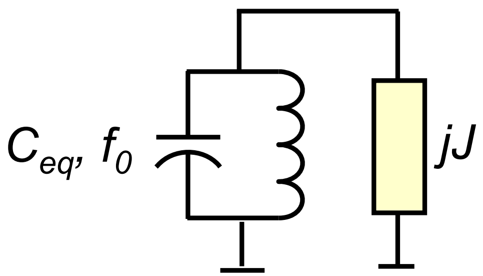




Even Eigenmode

$$f_e = f_0\left[\sqrt{\left(\frac{k}{2}\right)^2 + 1} + \frac{k}{2}\right]$$

$$f_e = f_0\left[\sqrt{\left(\frac{J}{2\omega_0 C_{eq}}\right)^2 + 1} + \frac{J}{2\omega_0 C_{eq}}\right]$$



Odd Eigenmode

$$f_o = f_0\left[\sqrt{\left(\frac{k}{2}\right)^2 + 1} - \frac{k}{2}\right]$$

$$f_o = f_0\left[\sqrt{\left(\frac{J}{2\omega_0 C_{eq}}\right)^2 + 1} - \frac{J}{2\omega_0 C_{eq}}\right]$$

Evaluation of *k* from f_e and f_o

From the expression of f_e and f_o:

$$\left(f_e - f_o\right) = f_0 \frac{J}{\omega_0 C_{eq}} = f_0 \cdot k$$

$$\left(f_e + f_o\right)^2 = 4 f_0 \left(1 + \left(\frac{J}{2\omega_0 C_{eq}}\right)^2\right) = 4 f_0 \left(1 + \left(\frac{k}{2}\right)^2\right) = 4 f_0 + \left(f_e - f_o\right)^2$$

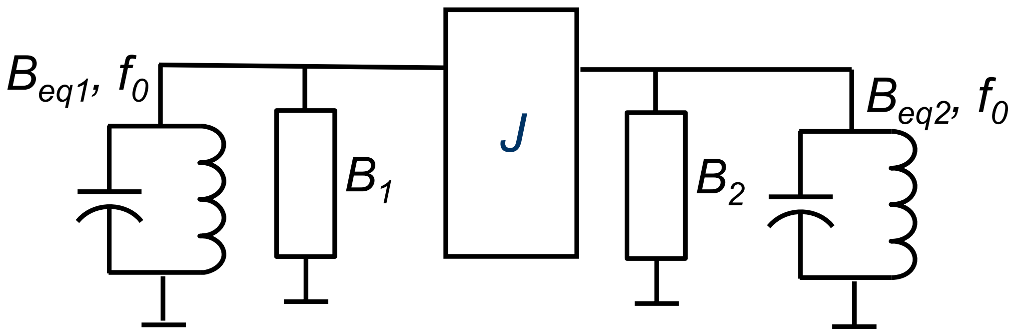
Then f_0 and *k* result:

$$f_0 = \sqrt{f_e \cdot f_o}, \qquad k = \frac{f_e - f_o}{f_0}$$

For small values of *k*, also the following expressions hold:

$$k \cong 2 \frac{\left(f_e - f_o\right)}{\left(f_e + f_o\right)} \cong \frac{\left(f_e^2 - f_o^2\right)}{\left(f_e^2 + f_o^2\right)}$$

Evaluation of k for asynchronously tuned coupled resonators



Note that the asynchronous tuning is implemented by the frequency-invariant susceptances (B_1, B_2).

In this case the symmetry cannot be exploited for computing the eigenvalues of the networks. We impose instead the resonance condition at the same time at each resonator terminal ($\Omega=(f/f_0-f_0/f)$:

$$B_{eq1}\bar{\Omega}+B_1-\frac{J^2}{B_{eq2}\bar{\Omega}+B_2}=0 \qquad B_{eq2}\bar{\Omega}+B_2-\frac{J^2}{B_{eq1}\bar{\Omega}+B_1}=0$$

Both equations have the same solutions in Ω:

$$\bar{\Omega} = \left(\Omega_A, \Omega_B\right) = -\frac{1}{2}\left(\frac{B_1}{B_{eq1}} + \frac{B_2}{B_{eq2}}\right) \pm \sqrt{\frac{1}{4}\left(\frac{B_1}{B_{eq1}} + \frac{B_2}{B_{eq2}}\right)^2 + \frac{J^2 - B_1 B_2}{B_{eq1} B_{eq2}}}$$

We assume again $k^2 = J^2/(B_{eq1}B_{eq2})$. Moreover, assuming f_{01} and f_{02} the resonances of the two resonators with B_1 and B_2, it has:

$$\Omega_1 = -\frac{B_1}{B_{eq1}} = \left(\frac{f_{01}}{f_0} - \frac{f_0}{f_{01}}\right), \qquad \Omega_2 = -\frac{B_2}{B_{eq2}} = \left(\frac{f_{02}}{f_0} - \frac{f_0}{f_{02}}\right)$$

Substituting in the previous equation:

$$\left(\Omega_A, \Omega_B\right) = \frac{1}{2}\left(\Omega_1 + \Omega_2\right) \pm \sqrt{\frac{1}{4}\left(\Omega_1 - \Omega_2\right)^2 + k^2}$$

Solving for k:

$$k = \sqrt{\left(\frac{\Omega_A - \Omega_B}{2}\right)^2 - \left(\frac{\Omega_1 - \Omega_2}{2}\right)^2}$$

Note that Ω_A and Ω_B are obtained from the eigenvalues f_A and f_B (computed with EM software):

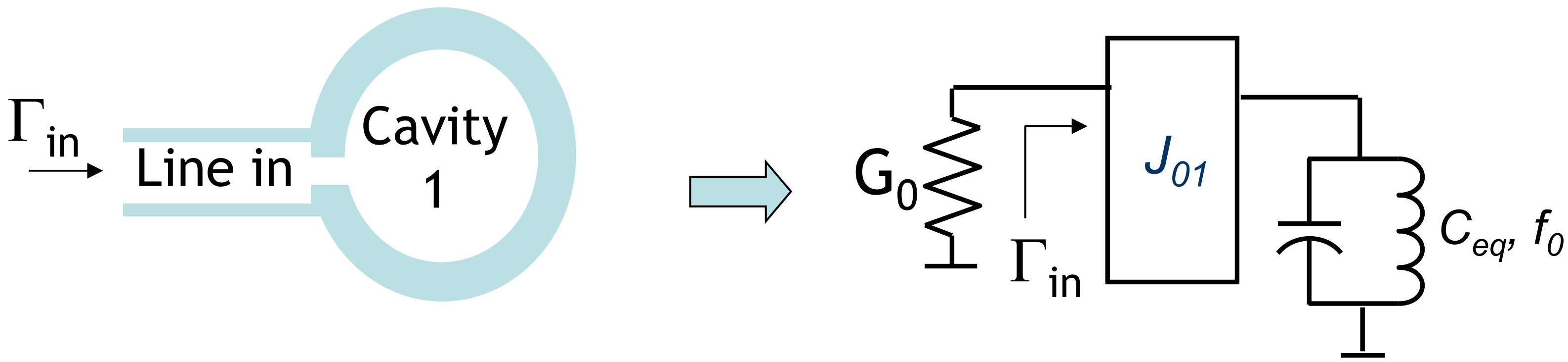
$$\Omega_A = \left(\frac{f_A}{f_0} - \frac{f_0}{f_A} \right), \qquad \Omega_B = \left(\frac{f_B}{f_0} - \frac{f_0}{f_B} \right)$$

Also the frequency f0 can be computed as function of the previous frequencies:

$$f_0 = \sqrt{\frac{f_{01} + f_{02} - f_A - f_B}{1/f_{01} + 1/f_{02} - 1/f_A - 1/f_B}}$$

Note that Beq_1 and Beq_2 are both computed at f0.
Moreover the coupling coefficient is the same of the two cavities tuned at f_0 (i.e. with B_1=B_2=0)

Evaluation of Q_E



$$\Gamma_{in} = \frac{G_0 - \left(J_{0,1}^2 / \left(B_{eq} \cdot F\right)\right)}{G_0 + \left(J_{0,1}^2 / \left(B_{eq} \cdot F\right)\right)} = \frac{1 - \left(1/\left(jF \cdot Q_E\right)\right)}{1 + \left(1/\left(jF \cdot Q_E\right)\right)} = \frac{jF \cdot Q_E - 1}{jF \cdot Q_E + 1}$$

$$B_{eq} = \omega_0 C_{eq}$$

$$F = \frac{f}{f_0} - \frac{f_0}{f}$$

$$Q_E = \frac{B_{eq}}{J_{01}^2 / G_0}$$

$$\angle\Gamma_{in} = \pi - 2\tan^{-1}\left(F \cdot Q_E\right)$$

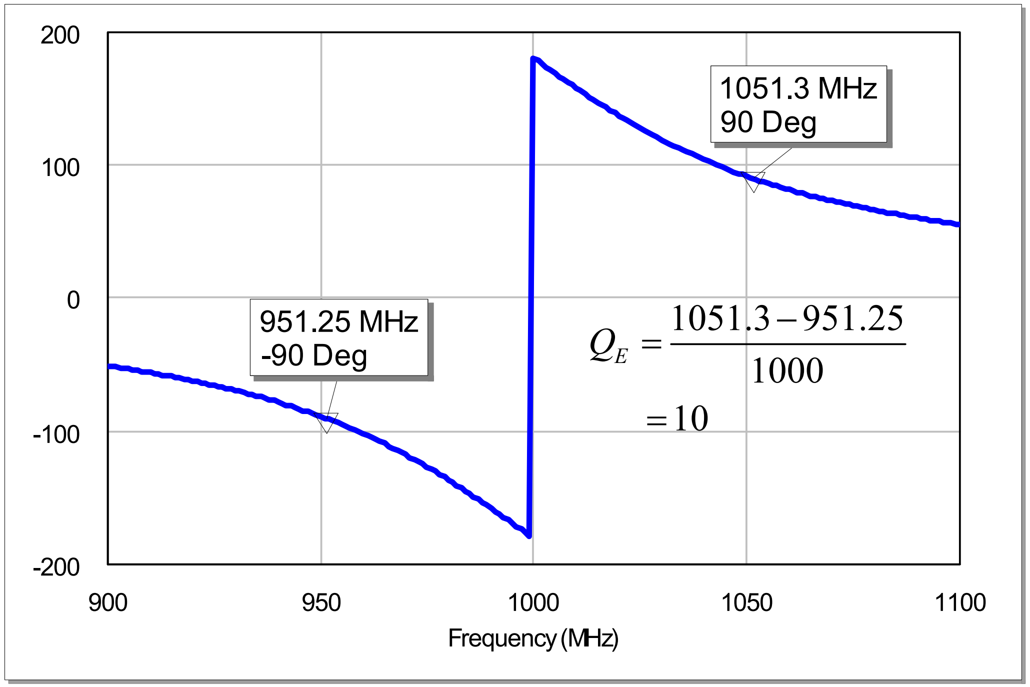
$$F_{+1} Q_E = 1 \quad \Rightarrow \quad \angle\Gamma_{in} = \frac{\pi}{2} \quad \Rightarrow \quad f_{+1} = f_0 \left(\frac{1}{2Q_E} + \sqrt{\left(\frac{1}{2Q_E}\right)^2 + 1} \right)$$

$$F_{-1} Q_E = -1 \quad \Rightarrow \quad \angle\Gamma_{in} = \frac{3\pi}{2} \quad \Rightarrow \quad f_{-1} = f_0 \left(-\frac{1}{2Q_E} + \sqrt{\left(\frac{1}{2Q_E}\right)^2 + 1} \right)$$

Evaluation of Q_E (cont.)

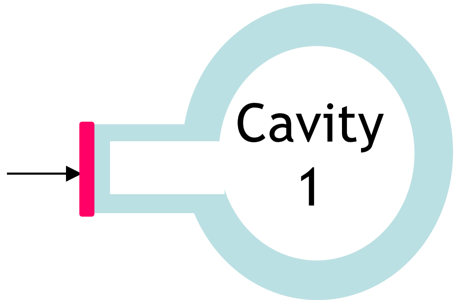
$$\boxed{Q_E = \frac{f_0}{f_{+1} - f_{-1}}}$$

f_{+1} and f_{-1} represent the frequencies around f_0 where the difference of Γ_{in} phase is equal to π.



Evaluation of Q_E from eigenmode analysis

Boundary condition=R0



Search of the first eigemode frequency (coincides with the resonant frequency)

Eigenmode analysis determines, other than the eigen-frequencies, also the corresponding Q. Performing a lossless analysis (ideal conductors and dielectrics) the evaluated Q is just the external Q of the resonator

Filter design using k and Q_E computed from eigen- frequencies of coupled cavities

- The cavities are selected and dimensioned for resonating at f_0 in absence of couplings
- For each pair of (identical) coupled cavities, a graph reporting k vs. a geometrical coupling dimension is generated. Accurate EM numerical methods should be used for the computations (eigenmode determination)
- The same is made for the coupling between the first (last) cavity and external load. The graph of Q_E vs. a geometrical dimension is realized
- The required values of $k_{i,j}$ and Q_E are determined for the filter to be designed using the general design equations
- The dimension of each coupling element is determined by the previously generated graphs

Limits of the method

- The main source of inaccuracy is the disregard of all the couplings in each cavity excluded the one to be dimensioned
- Another source of inaccuracy arises when the cavities are not all equal each others or are tuned at different frequencies (equations can be suitably modified but accuracy decreases)
- The resonance frequencies of the cavities does not remain at f_0 as the coupling varies
- The accuracy is then good only when the couplings are very small, which means small bandwidth filters (< 1-2%)
- It can be however used as a starting point for subsequent more accurate refining techniques

Is numerical optimization based on full wave modeling a convenient approach?

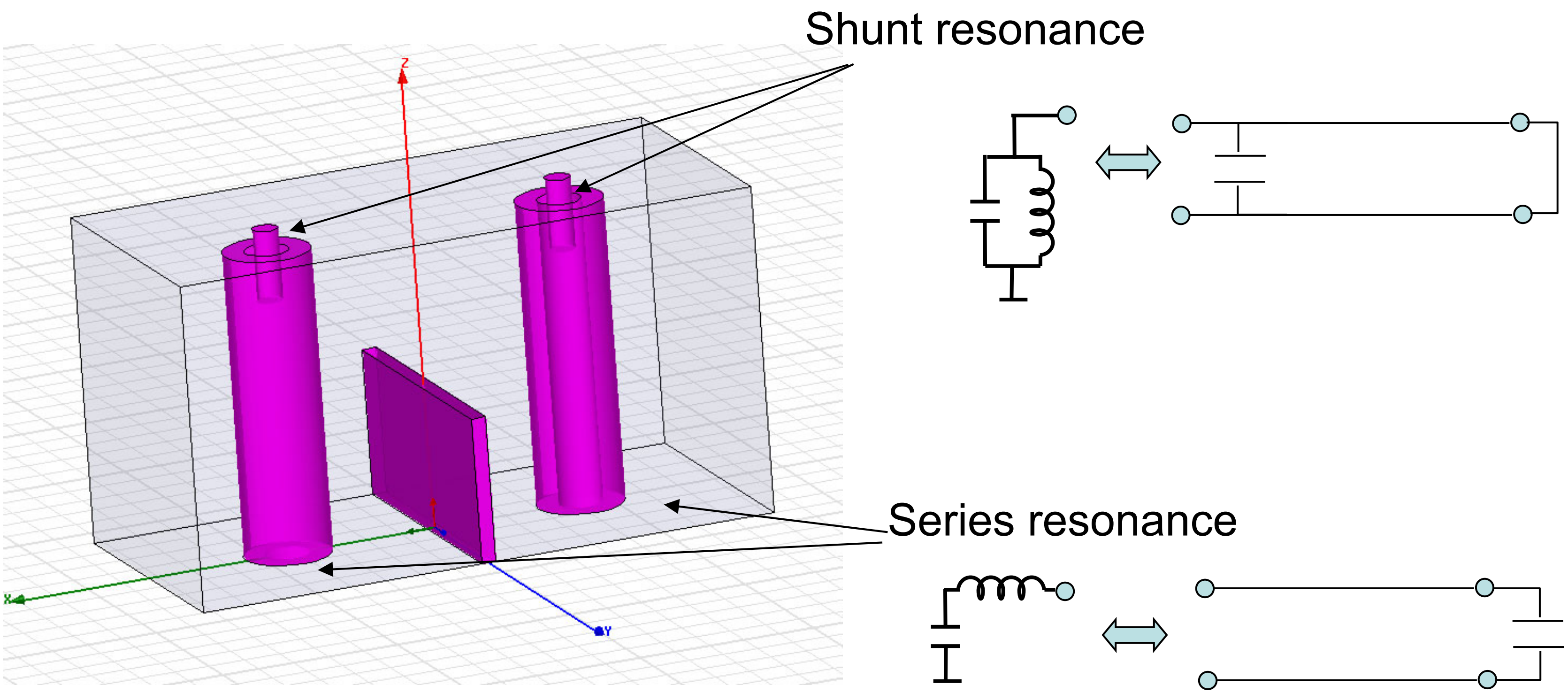
- The design refinement based on optimization of the filter response requires a very accurate EM modeling of the physical structure (FEM method is the most used in commercial simulators)
- The structure discretization (meshing) poses a limit to the attainable accuracy (the choice of the mesh density should be made with reference to the fabrication tolerances)
- The sensitivity of the variables controlling the cavities resonance and coupling coefficients is in general very different; a global optimization, which operates on all geometrical variables, usually gives very poor results
- A brute-force numerical optimization is also not convenient for the huge computer time requested (without the certainty of convergence to an acceptable result)

Mixing circuit and EM simulations for coupling coefficients evaluation

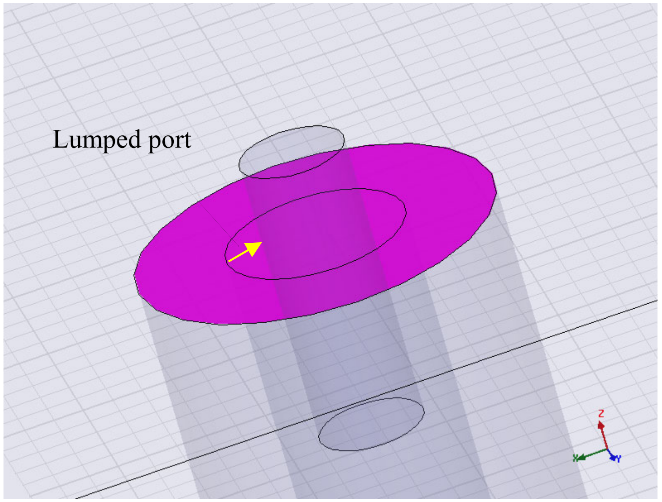
- To reduce computation time and increase flexibility, the evaluation of coupling coefficients can be performed through a suitable mixing of EM and circuit simulations
- With this approach the scattering parameters of the coupled cavities are evaluated with the EM simulator while the circuit simulator extract the coupling coefficients, taking into account both possible mistuning and structural differences of the cavities

EM simulations: identify reference ports

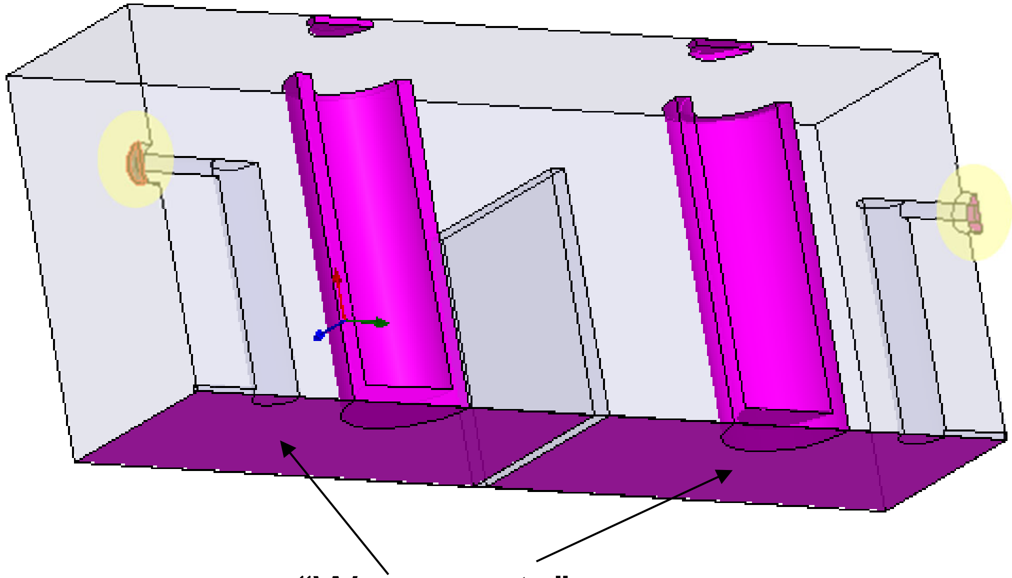
To obtain the scattering parameters from EM simulations, suitable sections must be identified in the simulated coupled cavities. These sections represent the *ports* of the equivalent circuit model where a series or a shunt resonance is observed



Ports type in the EM simulations



“Lumped port”



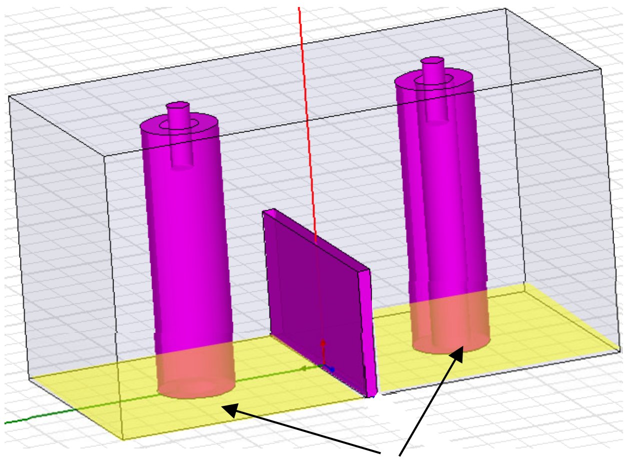
“Wave ports”

Wave ports are the most known and used. The wave port is defined by a bounded plane on the outer boundary of the structure. At these ports the mode excited is the one of the waveguide which has the same cross-section of the port.

The lumped ports impose a constant voltage across a small gap inside a structure. Should be used carefully because it is not easy to predict what mode is actually excited in the cavity

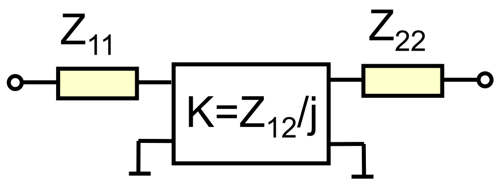
EM Simulation of the coupled cavities

According to the choice of reference sections, the EM simulated coupled cavities can be represented with the equivalent circuit derived from the Z or Y params. In the case of the considered coaxial structure:



Reference Sections

EM Simulation
(**S** Matrix)

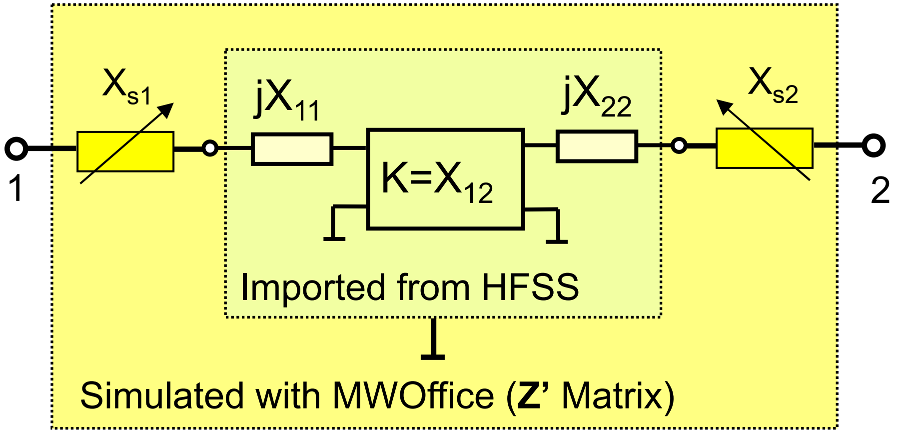


Impedance Matrix **Z** obtained from S matrix

$Z_{11}(f_1)=0 \qquad Z_{22}(f_2)=0$

$f_1 \neq f_2 \neq f_0$

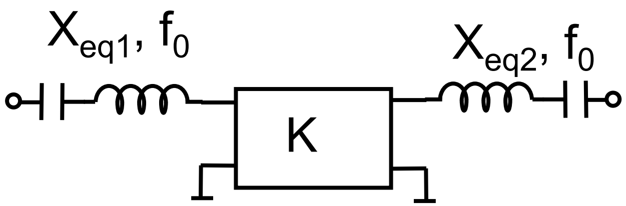
Evaluation of *k* with circuit simulation



$$Z'_{11} = jX_{s1} + jX_{11},\; Z'_{22} = jX_{s2} + jX_{22},\; Z'_{12} = jX_{12}$$

$$Z'_{11}(f_0) = 0 \;\Rightarrow\; X_{s1} = -X_{11}(f_0)$$

$$Z'_{22}(f_0) = 0 \;\Rightarrow\; X_{s2} = -X_{22}(f_0)$$



$$X_{eq1} = \omega_0 (1/2)(\partial X'_{11}/\partial\omega)_{\omega=\omega_0}$$

$$X_{eq2} = \omega_0 (1/2)(\partial X'_{22}/\partial\omega)_{\omega=\omega_0}$$

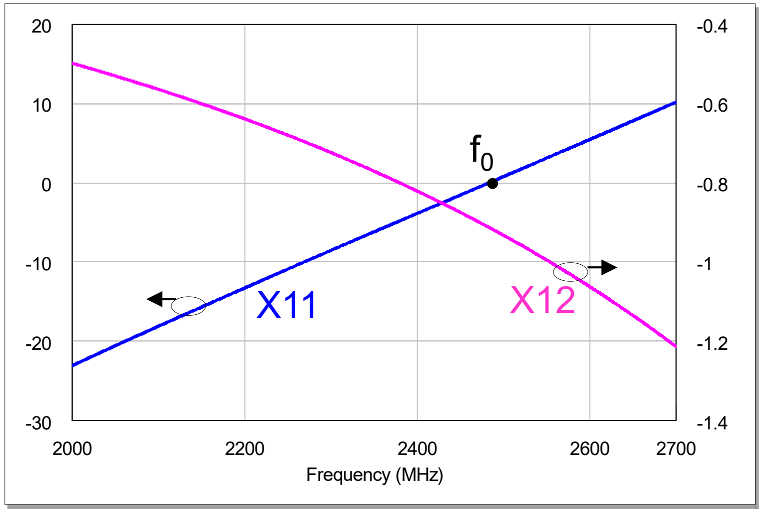
$$K = X'_{12}$$

$$\boxed{k = \frac{K}{\sqrt{X_{eq1} \cdot X_{eq2}}}}$$

The evaluation of X_{s1}, X_{s2} and k can be directly executed in the circuit simulator

Example with HFSS and MWOffice

Parameters $X_{11}=X_{22}$ and X_{12} from HFSS:



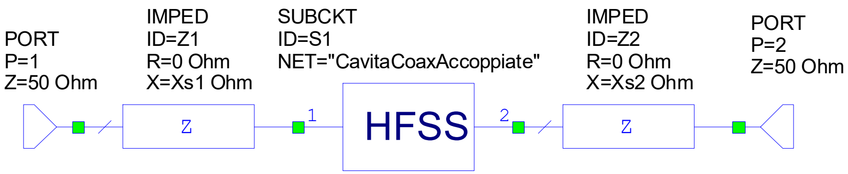
Equations for computing *k* (MWOffice)

Z11 = Coupled.$FPRJ:Z(1,1) Z12 = Coupled.$FPRJ:Z(1,2)

```
W=2*_PI*_FREQ X=imag(Z11)   K=imag(Z12)   I0=find_index(X,0)
xvet={X[I0-1],X[I0],X[I0+1]}  fvet={_FREQ[I0-1],_FREQ[I0],_FREQ[I0+1]}/1e6
f_new=stepped(_FREQ[I0-1], _FREQ[I0+1],(_FREQ[I0+1]-_FREQ[I0-1])/101)/1e6
Xint=interp(0,fvet,xvet,f_new)
Leq=.5*(der(Xint,2e6*_PI*f_new))
I1=find_index(Xint,0)
Xtot1=2e6*_PI*f_new[I1]*Leq[I1]            Xint_vs_f=plot_vs(Xint,f_new)
fris=f_new[I1]
k12=-K[I0]/(Xtot1)
```

fris: 2482
k12: 0.01579

Circuit simulated with MWOffice



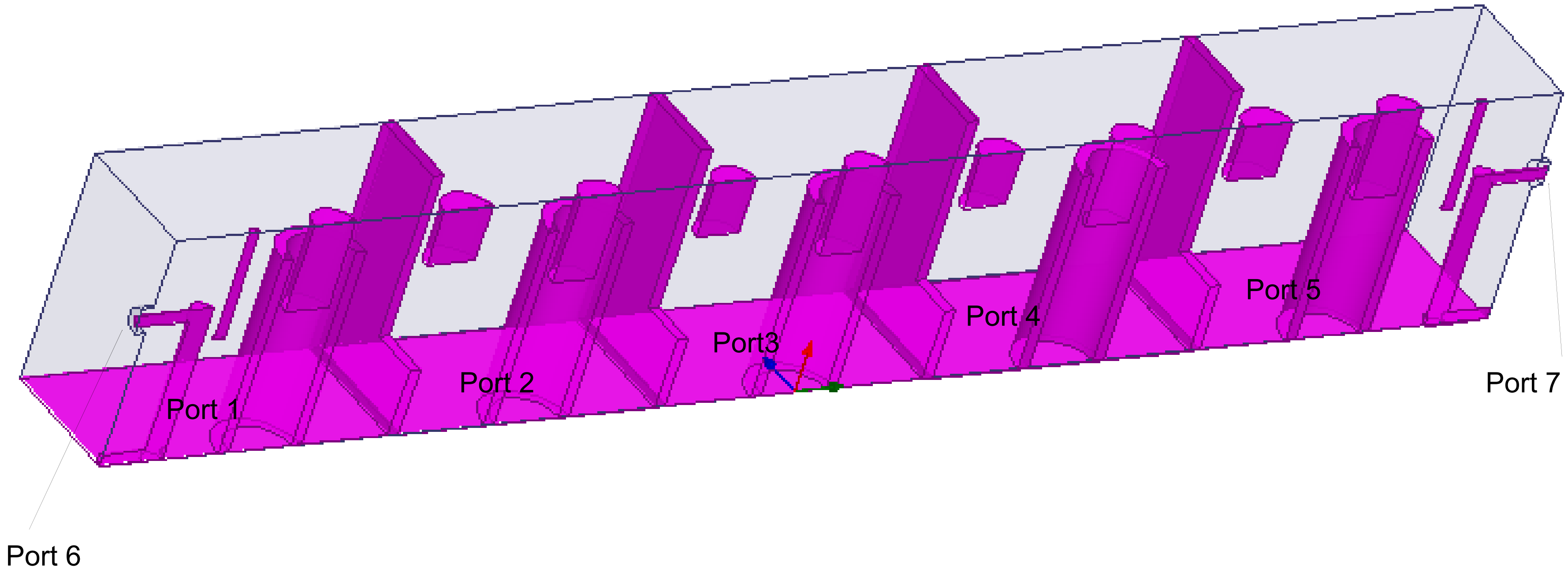
Xs1=0   Xs2=Xs1

Computed coupling coefficient

Graph 2

x Data (Unitless)	Re(Eqn()) fris.$FPRJ	Re(Eqn()) k12.$FPRJ
1	2482.4	0.01579

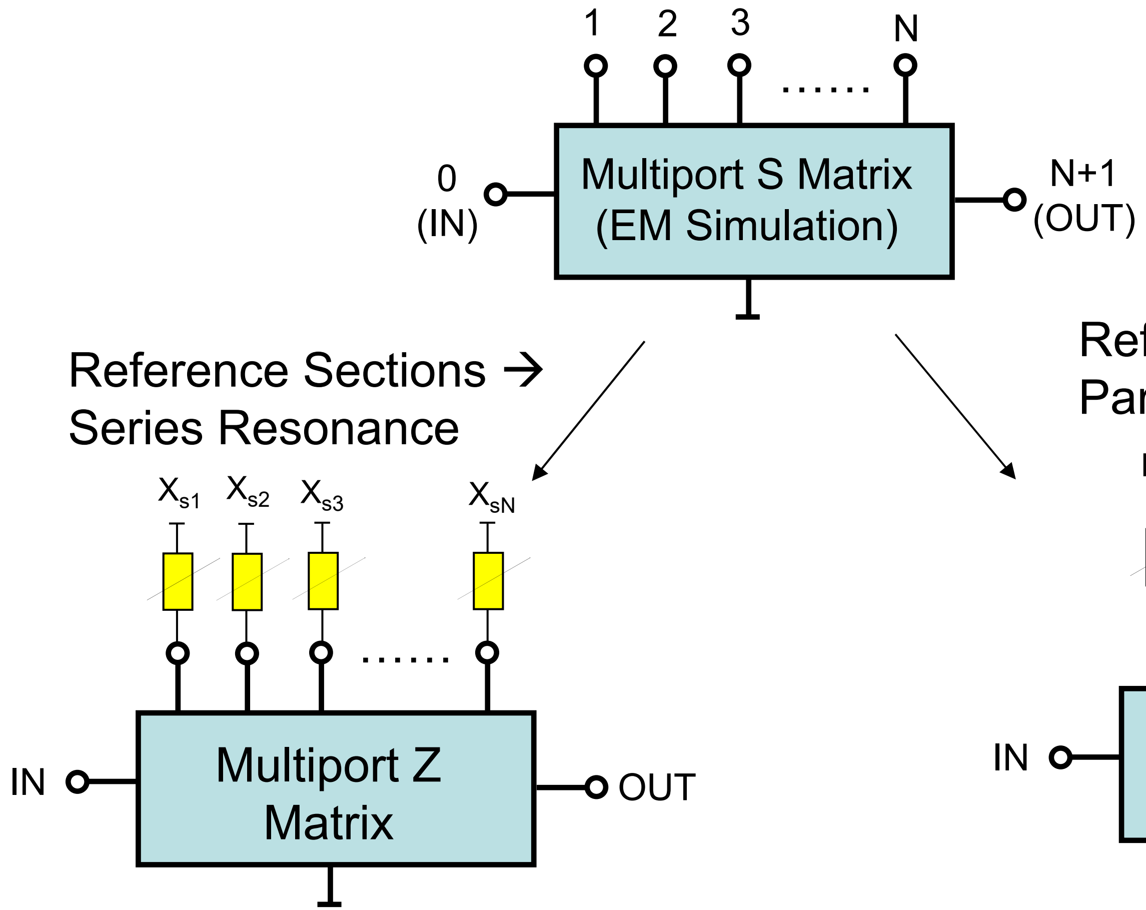
Overall S matrix of the filter at the cavities reference sections



Simulation is very fast because the resonators are loaded with the reference impedance of the ports (low Q)

Perfect cavities tuning is not requested

Fast computation of filter response from multi-port S matrix (EM simulation)

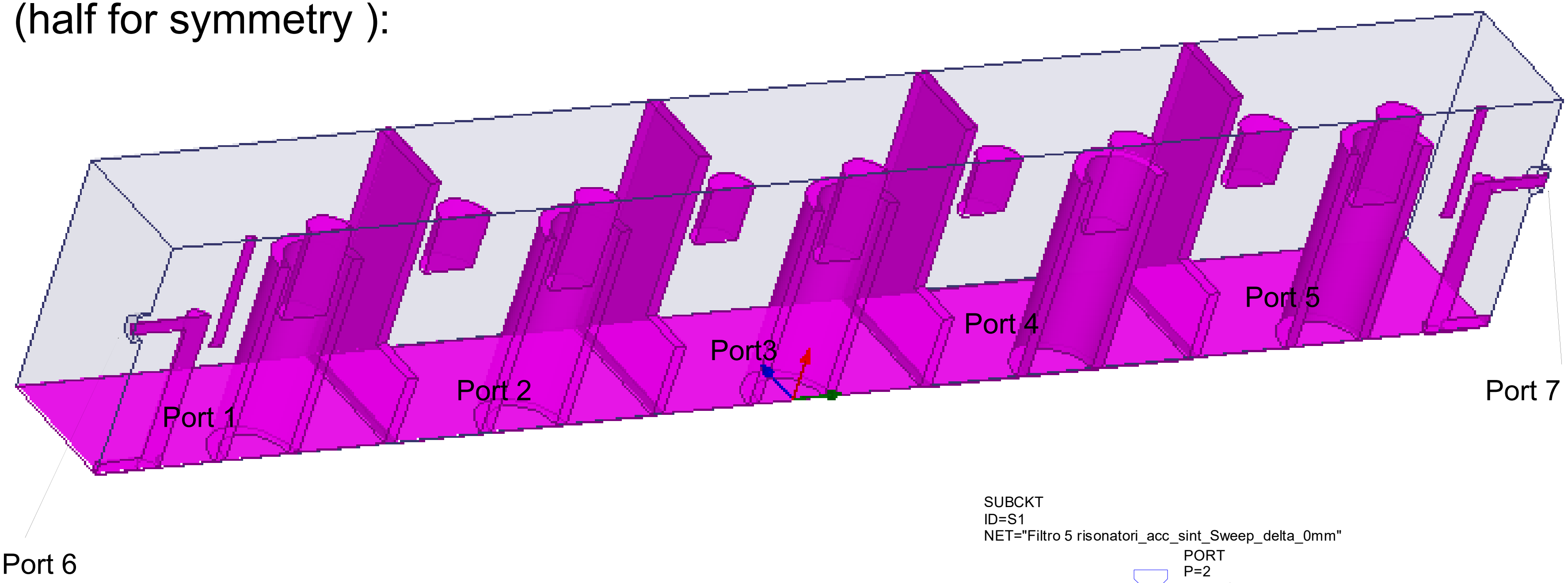


S matrix imported in a circuit simulator

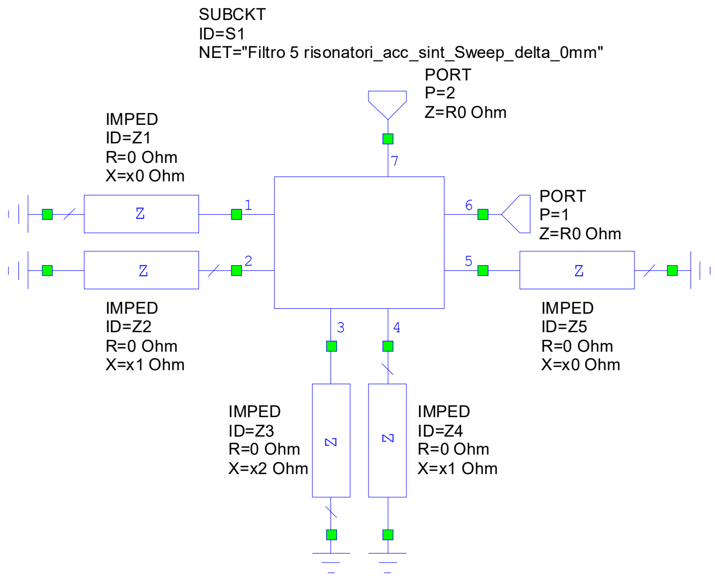
The tuning reactances X_{si} (B_{si}) are regulated in the circuit simulator in order to obtain X_{ii}=0 (B_{ii}=0). The response is then compute with the two-port circuit (input-output)

Example: 5 cavities filter (series model)

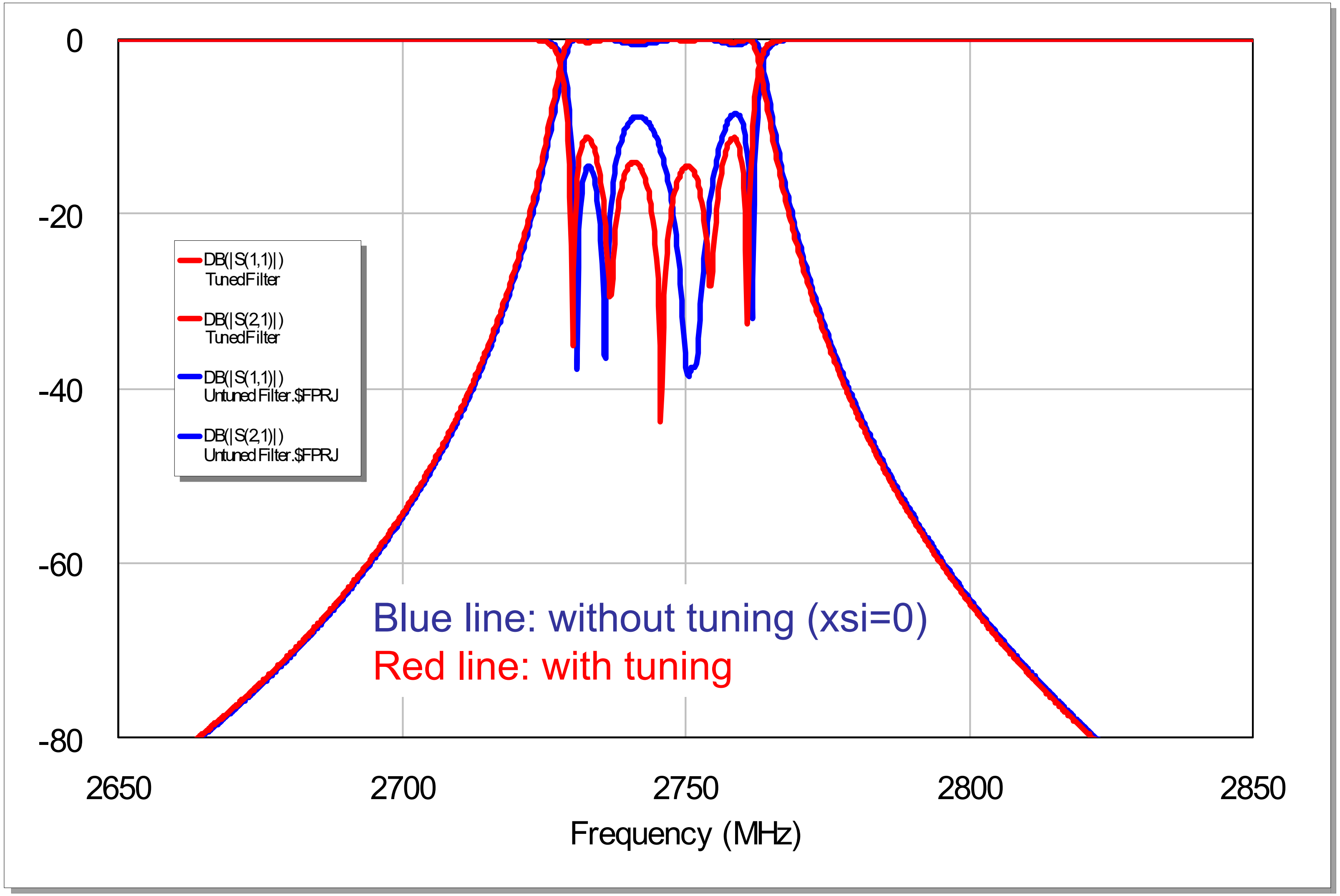
Structure simulated with HFSS
(half for symmetry):



Imported S parameters in MWOffice



Simulation results (with and without tuning reactances X_{si})



Extraction of coupling parameters from EM simulation (diagnosis)

- Input and output port are closed on reference impedance (it can be done either during EM simulation or in the circuit simulator)
- The equivalent resonators are tuned in the circuit simulator by imposing:

$$X_{ris,i} = \mathrm{Im}\left[Z_{i,i}\right]_{f=f_{0,i}} + X_{s,i} = 0$$

or

$$B_{ris,i} = \mathrm{Im}\left[Y_{i,i}\right]_{f=f_{0,i}} + B_{s,i} = 0$$

- $B_{eq,i}$ ($X_{eq,i}$) are computed at frequency f_0:

$$B_{eq,i} = \omega_0 \frac{1}{2} \left. \frac{\partial B_{ris,i}}{\partial \omega} \right|_{\omega=\omega_0} \quad \text{or} \quad X_{eq,i} = \omega_0 \frac{1}{2} \left. \frac{\partial X_{ris,i}}{\partial \omega} \right|_{\omega=\omega_0}$$

Note that this computation can be performed into the circuit simulator (elaborating simulations results)

- The coupling coefficients are then evaluated as:

$$k_{i,j} = \frac{b_{i,j}(f_0)}{\sqrt{B_{eq,i} \cdot B_{eq,j}}} \quad \text{or} \quad k_{i,j} = \frac{x_{i,j}(f_0)}{\sqrt{X_{eq,i} \cdot X_{eq,j}}}$$

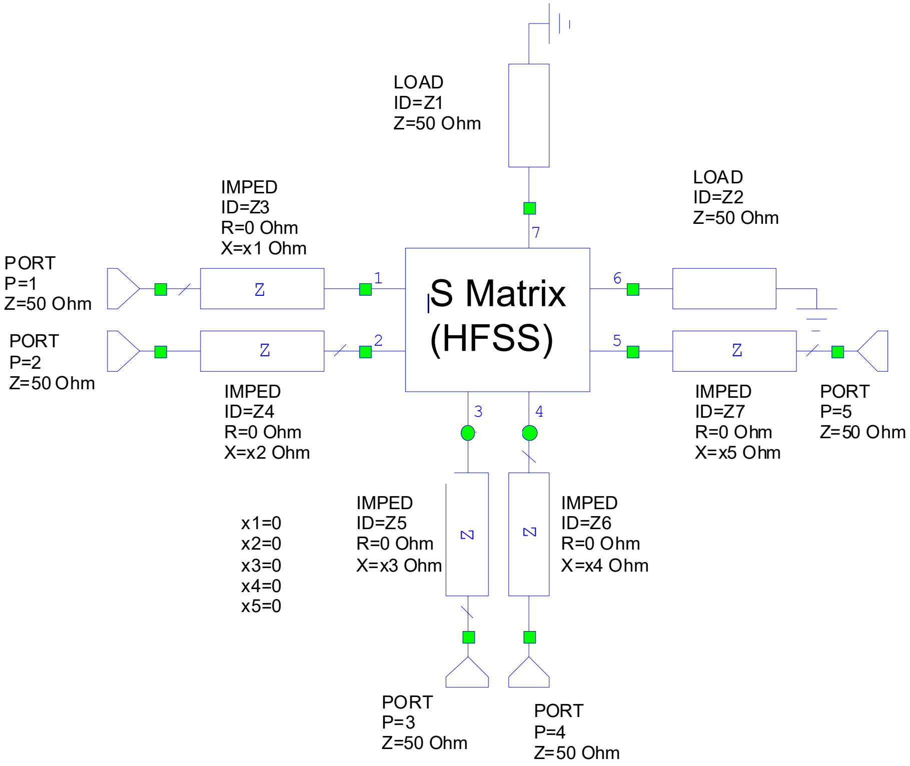
Note that spurious couplings can be also evaluated (i.e. couplings not present in the equivalent circuit of the filter)

- For resonators coupled with source/load the external Q is evaluated:

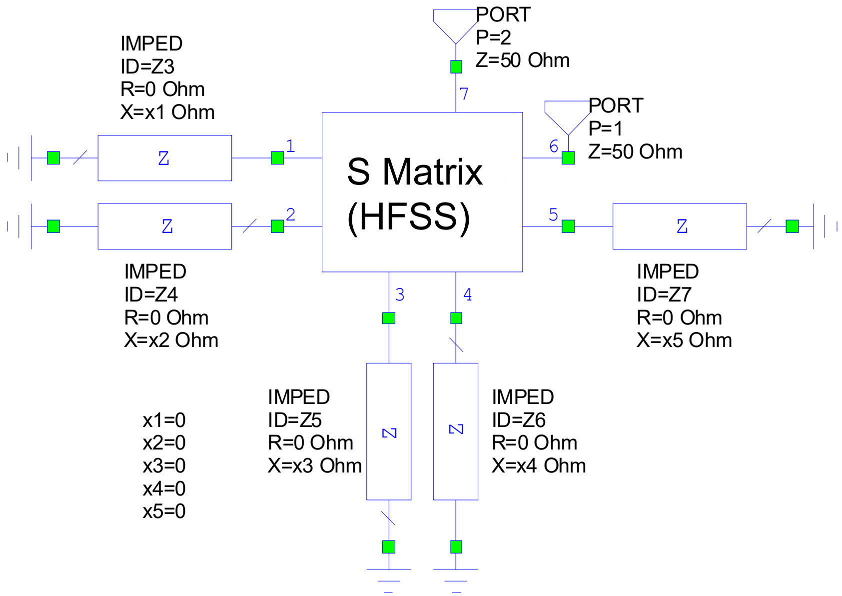
$$Q_{S,i} = \frac{B_{eq,i}}{\mathrm{Re}\left[Y_{i,i}\right]} \quad \text{or} \quad Q_{S,i} = \frac{X_{eq,i}}{\mathrm{Re}\left[Z_{i,i}\right]}$$

- The extracted parameters can be then compared with theoretical values (i.e. those obtained from the synthesis), identifying the deviations and correcting them by suitably modifying the dimensions of the coupling structures

Example: 5 resonators filter

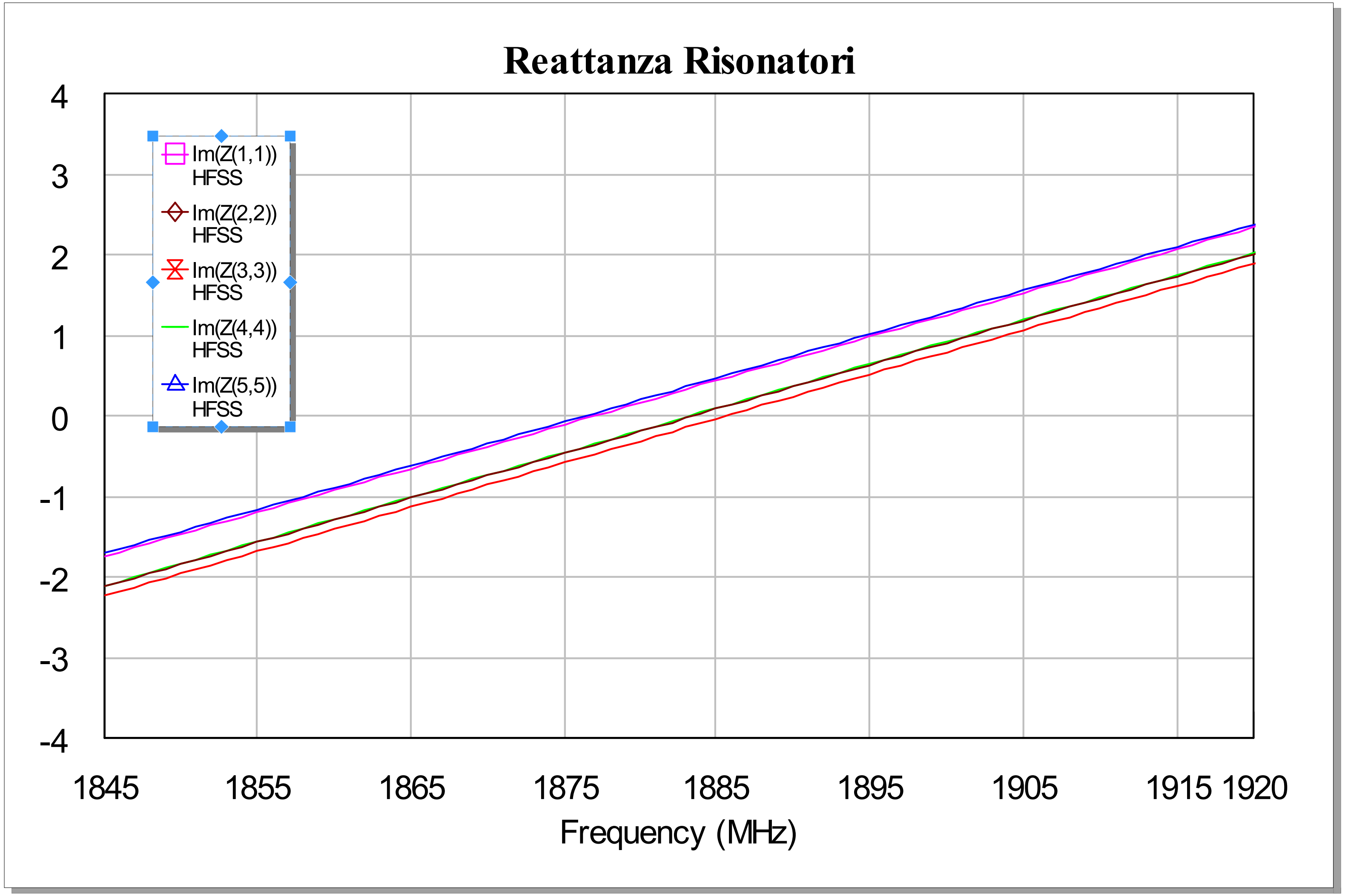


Parameters extraction



Analysis

Resonators reactances ($X_{i,i}$) with no tuning



Extracted Parameters

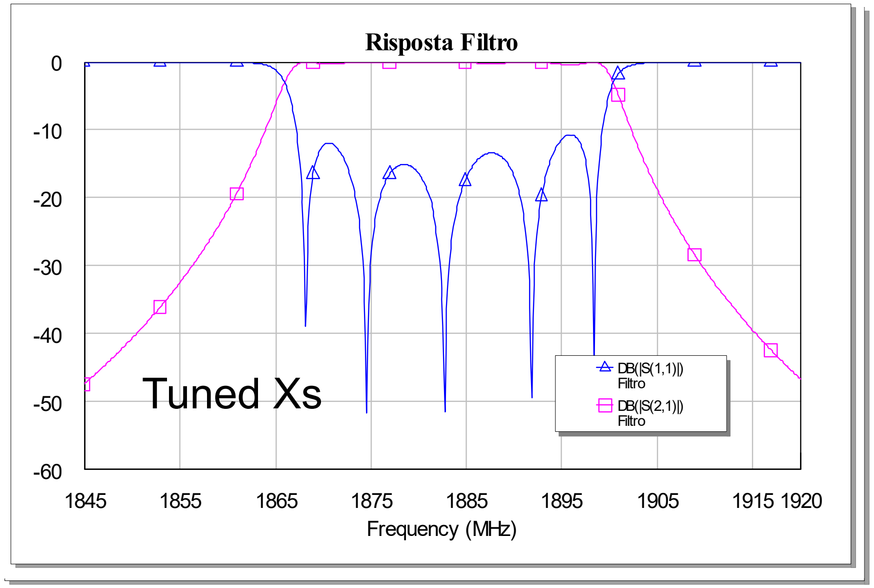
Resonance Frequencies (f_0=1885)				
fris1	fris2	fris3	fris4	fris5
1876.9	1883.4	1885.5	1883.2	1876.3

Coupling coefficients			
k12	k23	k34	k45
0.0122	0.0099061	0.0098636	0.012072

External Q Factors	
Qext1	Qext5
82.395	82.461

Tuning errors (resonators 1 e 5)

Tuned resonators



Smart optimization of the design (couplings only)

Starting point:

- Synthesized coupling parameters ($k_{ij,T}$, $f_{0,i}$, $Q_{ext,T}$)
- Graphs reporting the dependence of the coupling coefficients on a geometrical parameter of the coupling structures (2 cavities at a time, EM analysis)
- Initial dimensions of the coupling structures (obtained with the previous graphs) and S matrix of the overall filter (EM multiport simulation)

First operation:

- Interpolating functions are generated from the graphs of $k_{i,j}$ (and Q_{ext}):

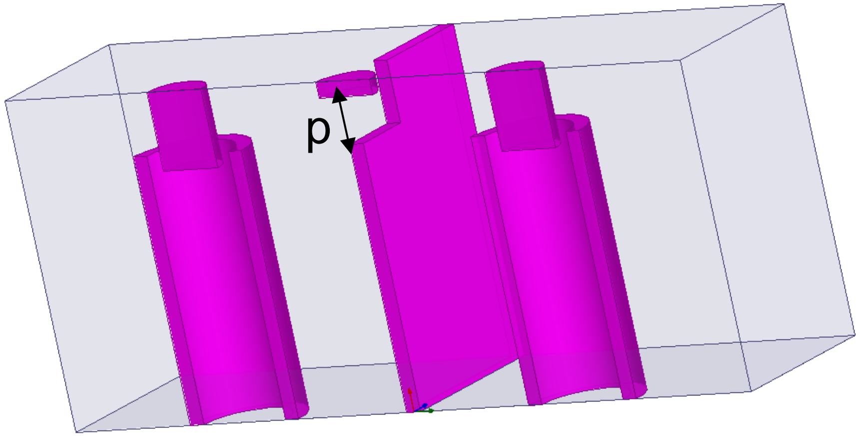
$$k_{i,j}=F_k\,(p_k)\;,$$

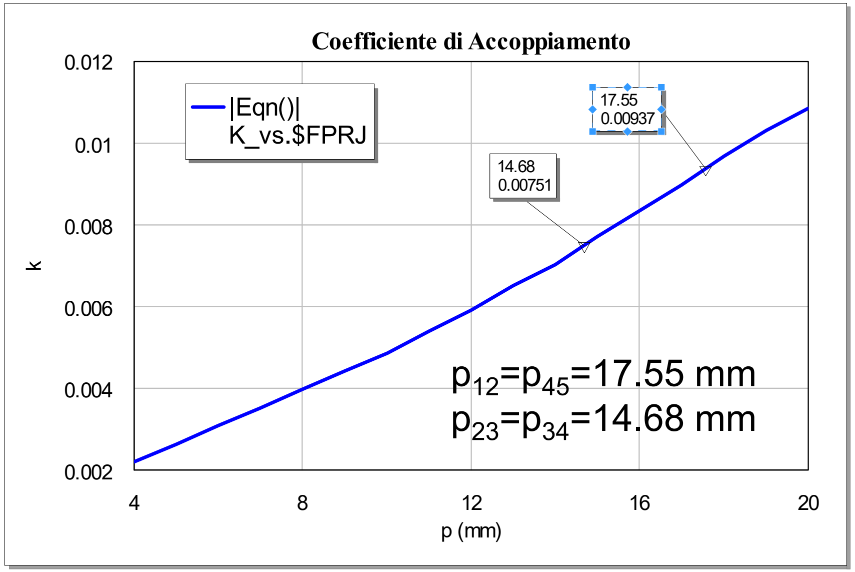
- A correcting factor (C_k) is introduced in the previous functions (it is initially set to 0):

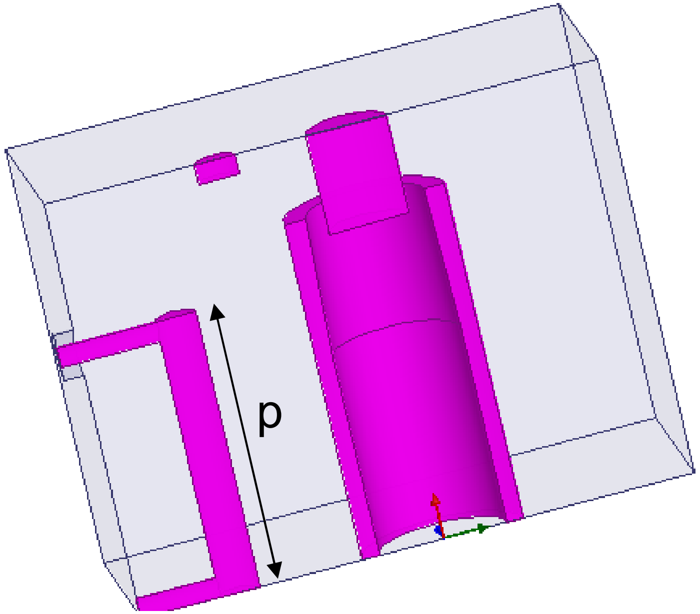
$$k_{i,j}=F_k\,(p_k)+C_k.$$

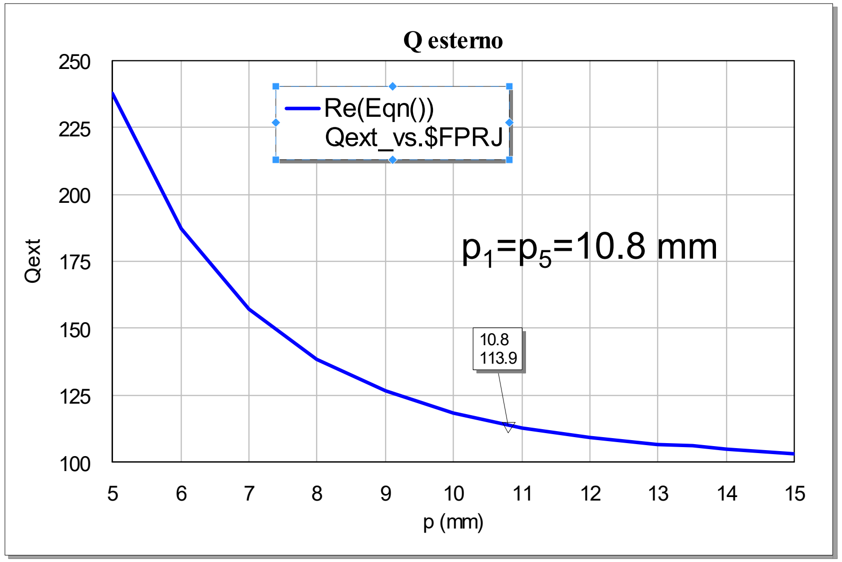
Note that C_k produces a vertical translation of the original curve $F_k\,(p_k)$

Graphs generation and initial dimensioning ($k_{ij,T}$=0.00937, 0.00751 Q_{ext}=113.9)









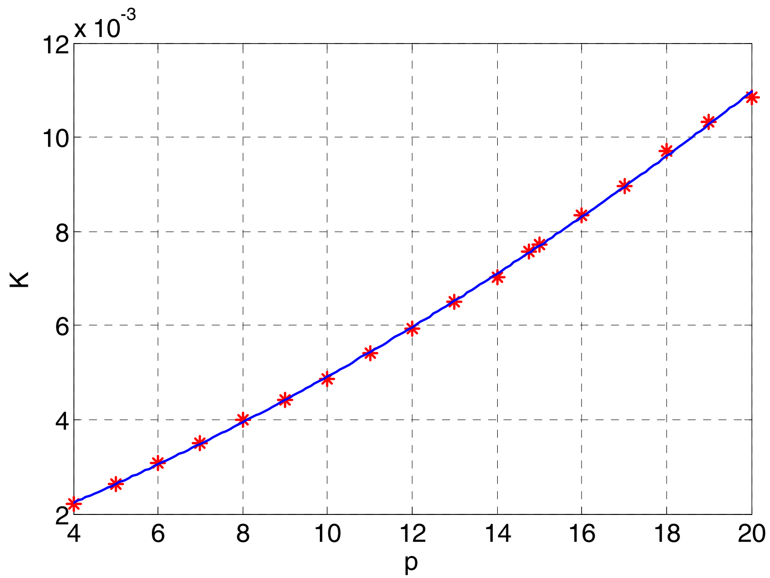
Polynomial interpolation

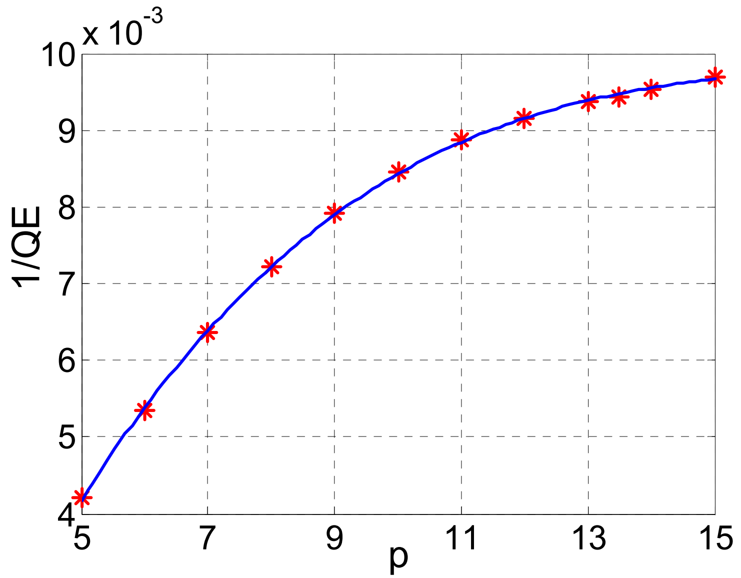
Coupling Coefficient:

$$k(p) = \left(0.0098 \cdot p^2 + 0.3094 \cdot p + 0.8392\right) \cdot 10^{-3}$$

External Q:

$$\left(1/Q_E(p)\right) = \left(0.00313 \cdot p^3 - 0.154 \cdot p^2 + 2.617 \cdot p - 5.448\right) \cdot 10^{-3}$$





Extraction of parameters from HFSS simulation and evaluation of correcting factors

Extracted parameters:

$k_{12,e}$=0.01144, $k_{23,e}$=0.0076, $Q_{ext,e}$=115.4

Correcting factors:

$$C_{12} = k_{12,e} - k_{12,T} = 0.0021, \qquad C_{23} = k_{23,e} - k_{23,T} = 9\text{e-}005$$

$$C_{ext} = \frac{1}{Q_{ext,e}} - \frac{1}{Q_{ext,T}} = -1.1412\text{e-}004$$

Corrected equations

$$k_{12}(p) = \left(0.0098 \cdot p^2 + 0.3094 \cdot p + 0.8392 + 2.1\right) \cdot 10^{-3}$$

$$k_{23}(p) = \left(0.0098 \cdot p^2 + 0.3094 \cdot p + 0.8392 + 0.09\right) \cdot 10^{-3}$$

$$\left(1/Q_E(p)\right) = \left(0.00313 \cdot p^3 - 0.154 \cdot p^2 + 2.617 \cdot p - 5.448 - 0.114\right) \cdot 10^{-3}$$

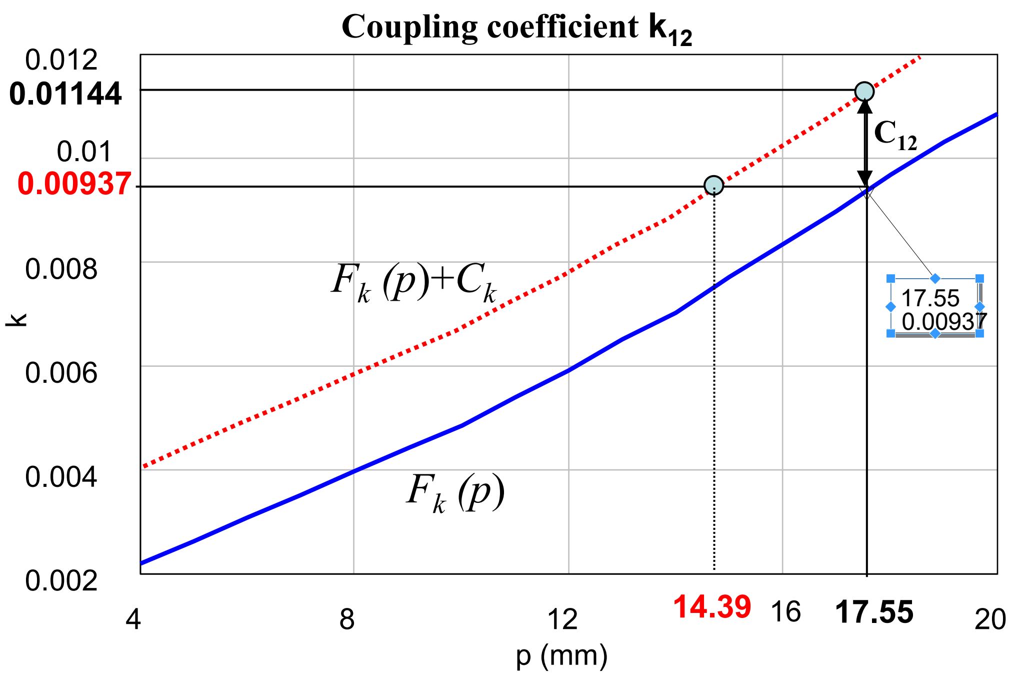
New estimation of dimensions

$$\left(0.0098\cdot p^2+0.3094\cdot p+0.8392+2.1\right)\cdot 10^{-3}=k_{12,T}\quad\Rightarrow\quad p=14.39\text{mm}$$

$$\left(0.0098\cdot p^2+0.3094\cdot p+0.8392+0.09\right)\cdot 10^{-3}=k_{23,T}\quad\Rightarrow\quad p=14.56\text{mm}$$

$$\left(0.00313\cdot p^3-0.154\cdot p^2+2.617\cdot p-5.448-0.114\right)\cdot 10^{-3}=$$

$$=\left(1/Q_{ext,T}(p)\right)\quad\Rightarrow\quad p=11.11\text{mm}$$



New simulation with HFSS

Using the new computed values of the dimensions p_k, a new simulation of the whole filter is made and the extracted coupling parameters result:

$$k_{12,e}=0.009,\ k_{23,e}=0.00747,\ Q_{ext,e}=113.8$$

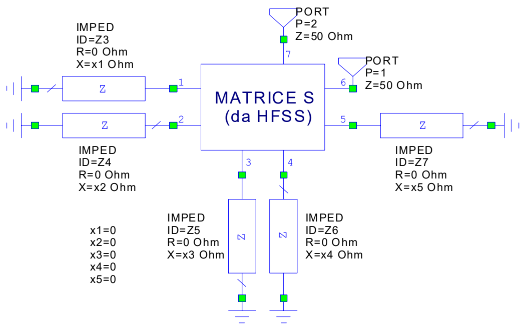
These are again compared with the requested values ($k_{i,j,T}$, $Q_{ext,T}$) and the correction procedure is repeated. The new values of dimensions result:

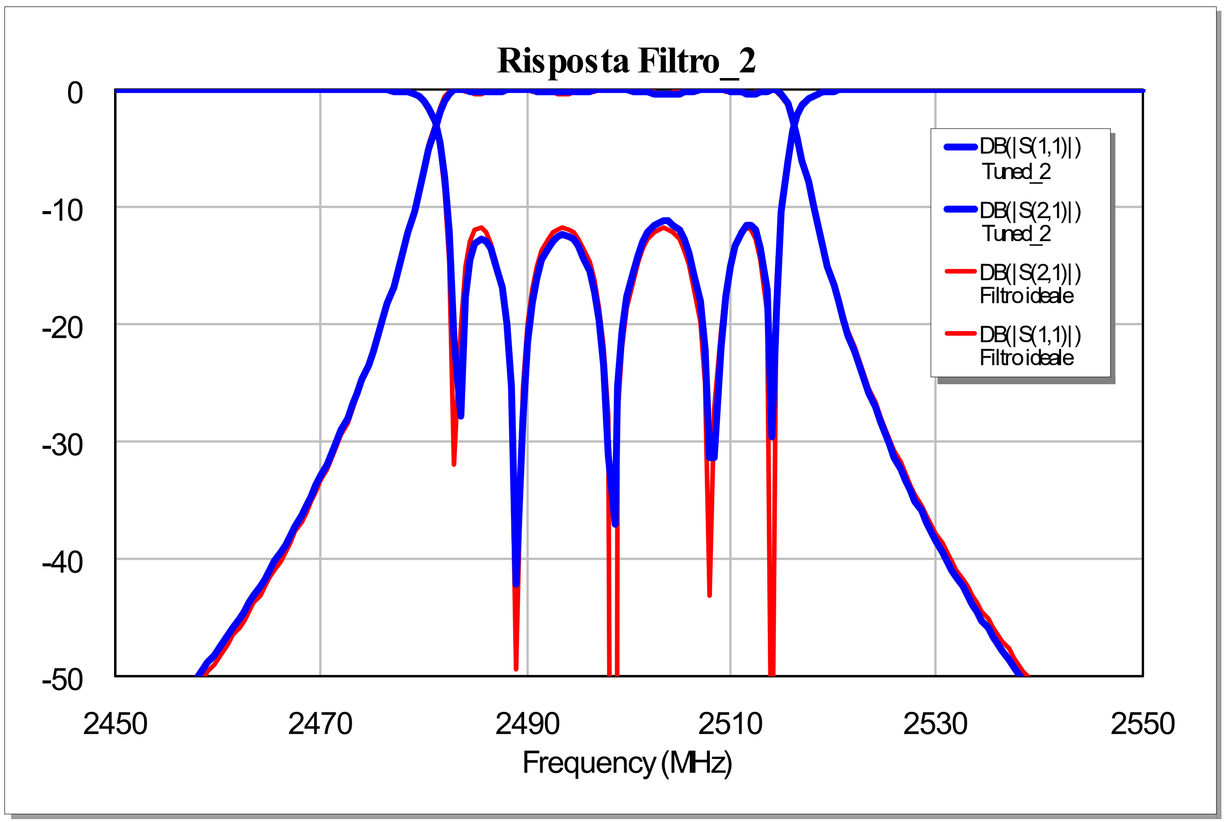
$p_{12}=p_{45}=14.93$ mm
$p_{23}=p_{34}=14.62$ mm

$p_1=p_5=11.1$ mm

A further iteration of the procedure is no more necessary as the corrected parameters do not present a further significant variation

Corrected Filter response (tuned)





Advantages of this design approach

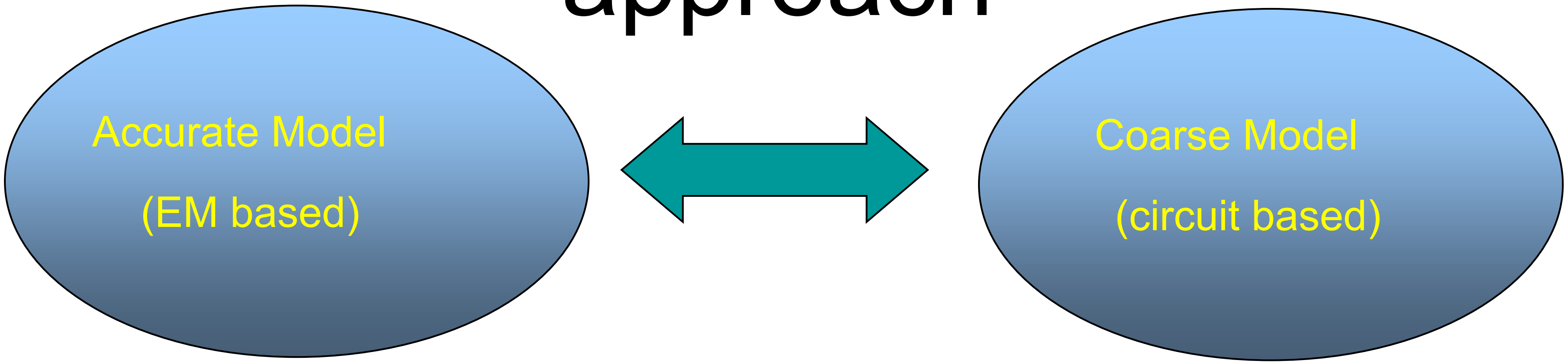
- It can be easily implemented practically
- As a starting point even the classical approximated design (based on even and odd resonance frequencies of coupled cavities) can be used
- It allows an accurate dimensioning without requiring numerical optimization (especially at EM level)
- Very few EM simulations are required

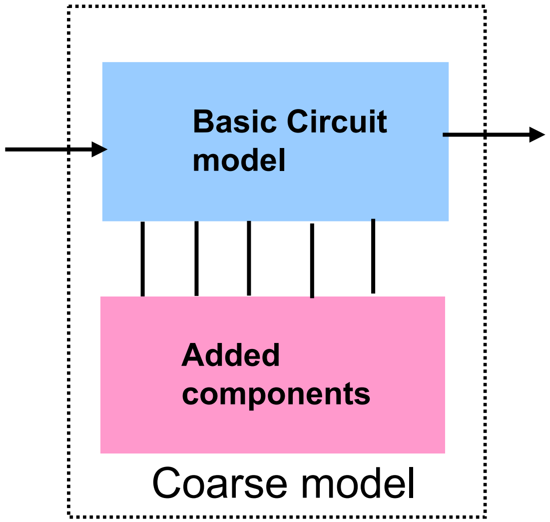
Limits of this approach

- It is based on the couplings parameters derived from lumped-element modeling
- Does not account for variation with frequency of the couplings
- Does not account for spurious couplings
- For the above reasons the final designed filter could not produce the desired response even if the extracted parameters have the correct value
- In some cases the computed dimensions may not converge (with bad initial design)

Space Mapping for Filter design

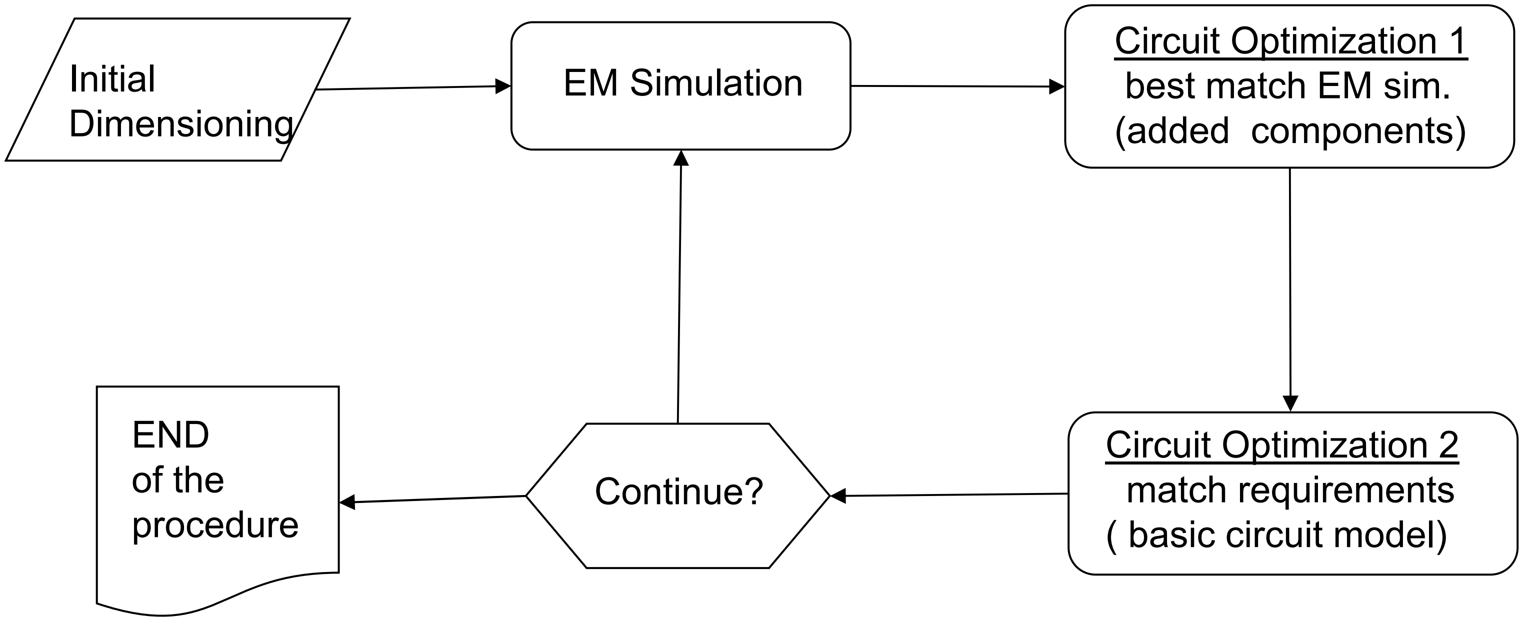
Space-mapping approach





- The components in the Basic Circuit model are defined through coarse functions of dimensions
- The added components are used for matching the Accurate Model response (using circuit optimization)

Space-mapping flow chart



Example: Design of an iris-coupled waveguide filter at 73 GHz

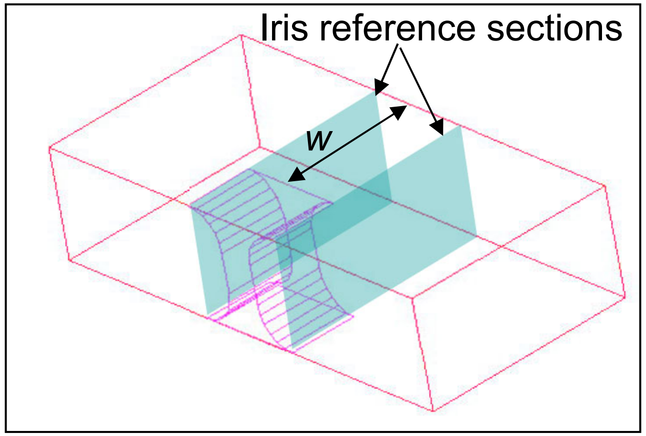
Specifications

N. of resonators: 6

Passband: 71 – 76 GHz

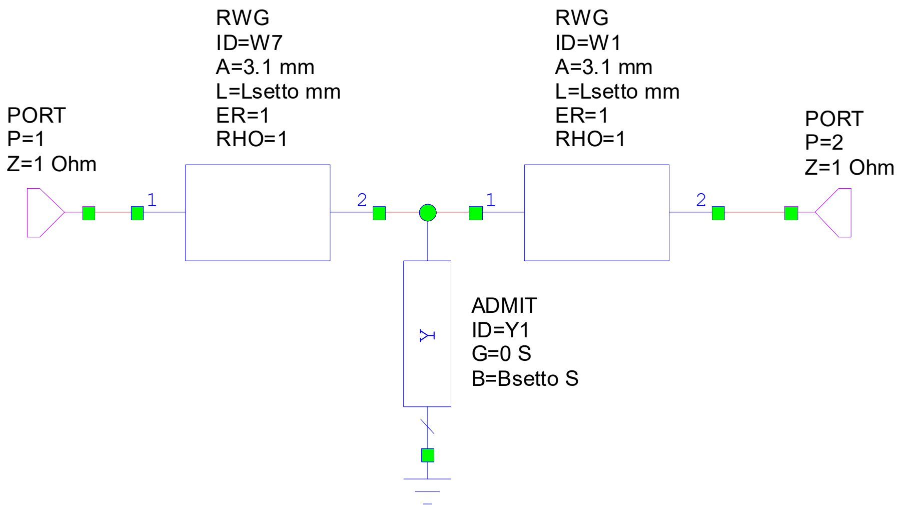
RL in passband: 20 dB

Tecnology: asymmetrical iris in rectangular waveguide (mode TE_{10}, a=3.1mm, b=1.55mm, f_{cutoff}=48.35 GHz)



Note: the iris presents rounded edges (due to the radius of the mill tool) which must be taken into account in the models derivation (both circuit and EM)
In this case the bending radius is 0.5 mm and the minimum thickness is 0.5 mm.

Model for the iris



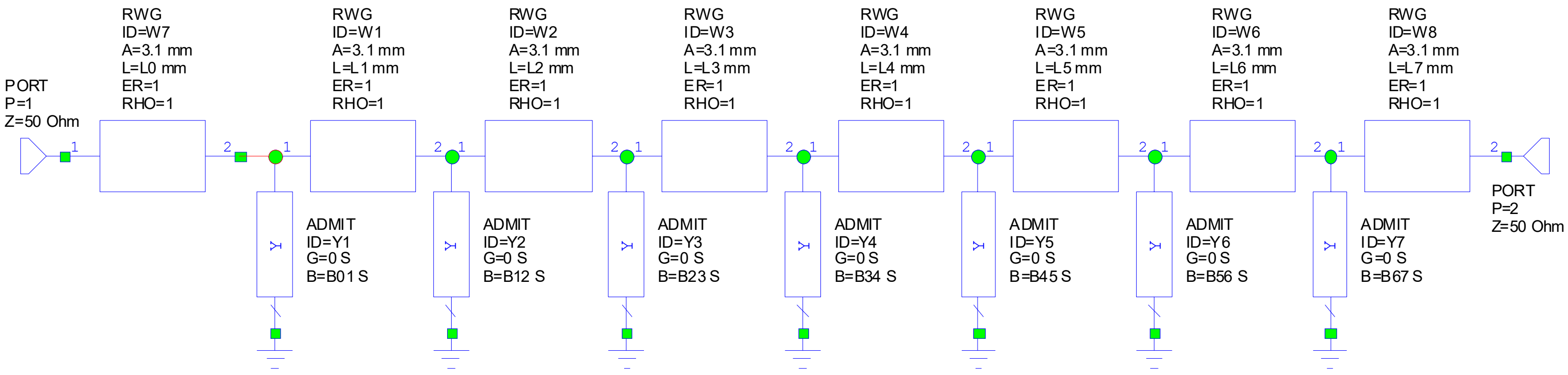
Parameters (functions of *w*,*f*):
L_{setto}, B_{setto}

Interpolating the results of EM simulations we have derived the following empirical relationships:

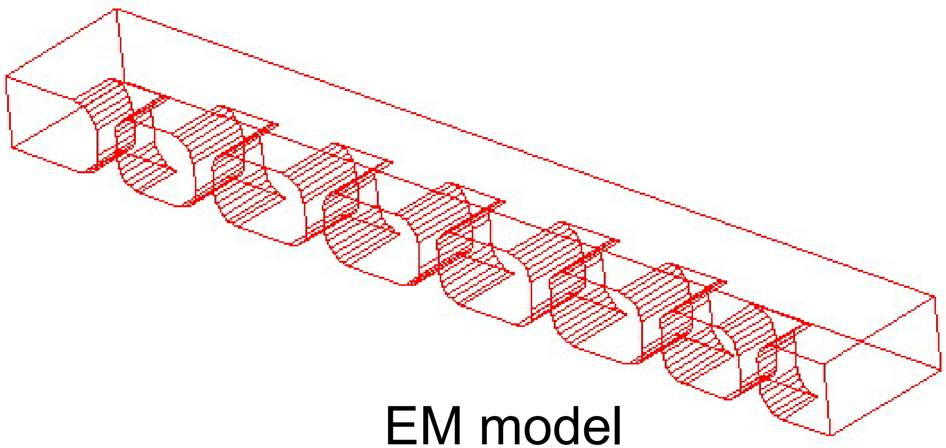
$$B_{setto} = B_0 \left(\frac{f_0^2 - f_c^2}{f^2 - f_c^2} \right)^{1.2}, \qquad B_0 = -37.87 \cdot w^3 + 114.68 \cdot w^2 - 121.155 \cdot w + 42.71$$

$$L_{setto} = L_0 \left(\frac{f^2 - f_c^2}{f_0^2 - f_c^2} \right)^{0.4}, \qquad L_0 = \frac{2\pi f}{c} \left(0.0012 \cdot w^2 - 0.2345 \cdot w + 0.1102 \right)$$

Initial filter design



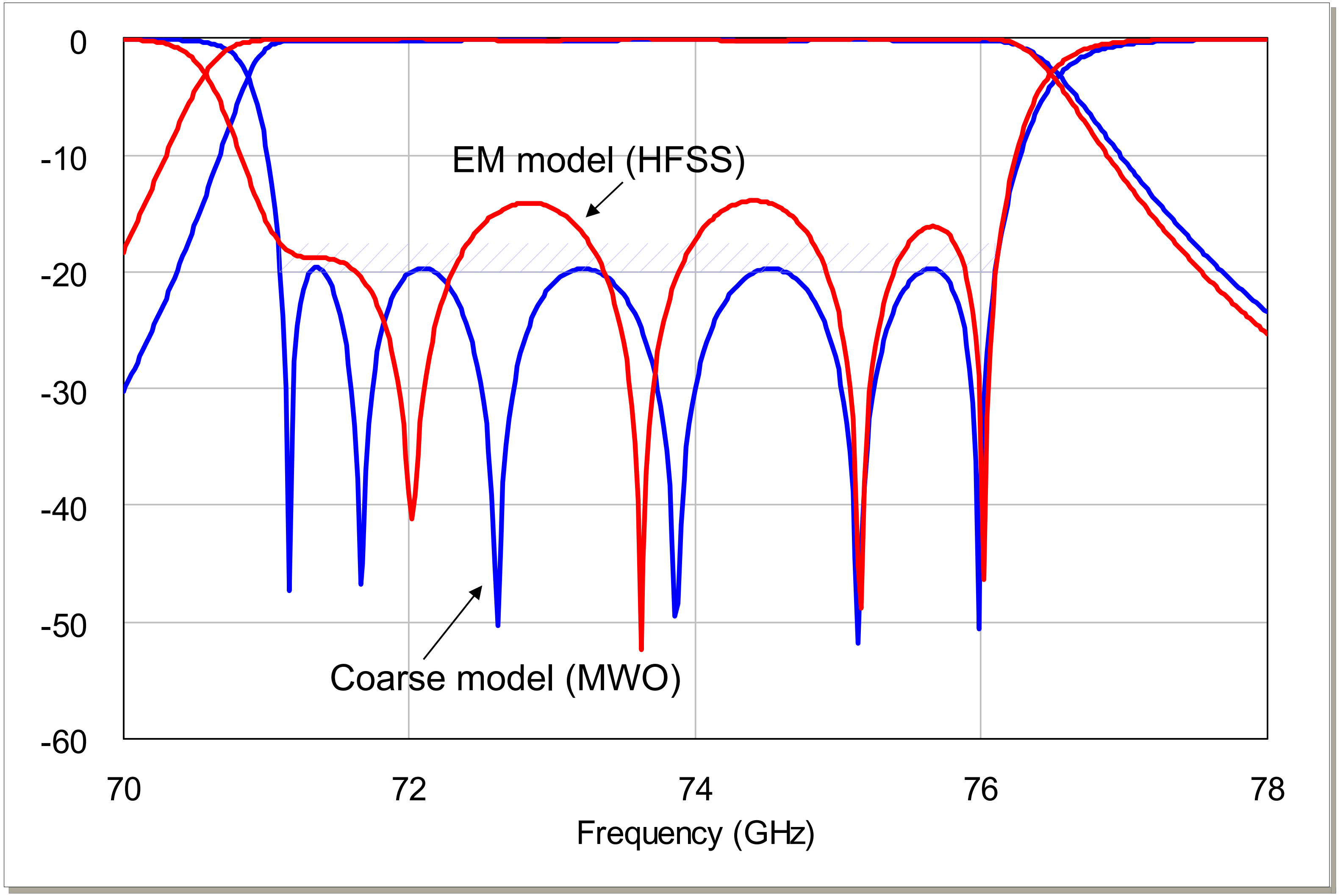
Basic circuit model



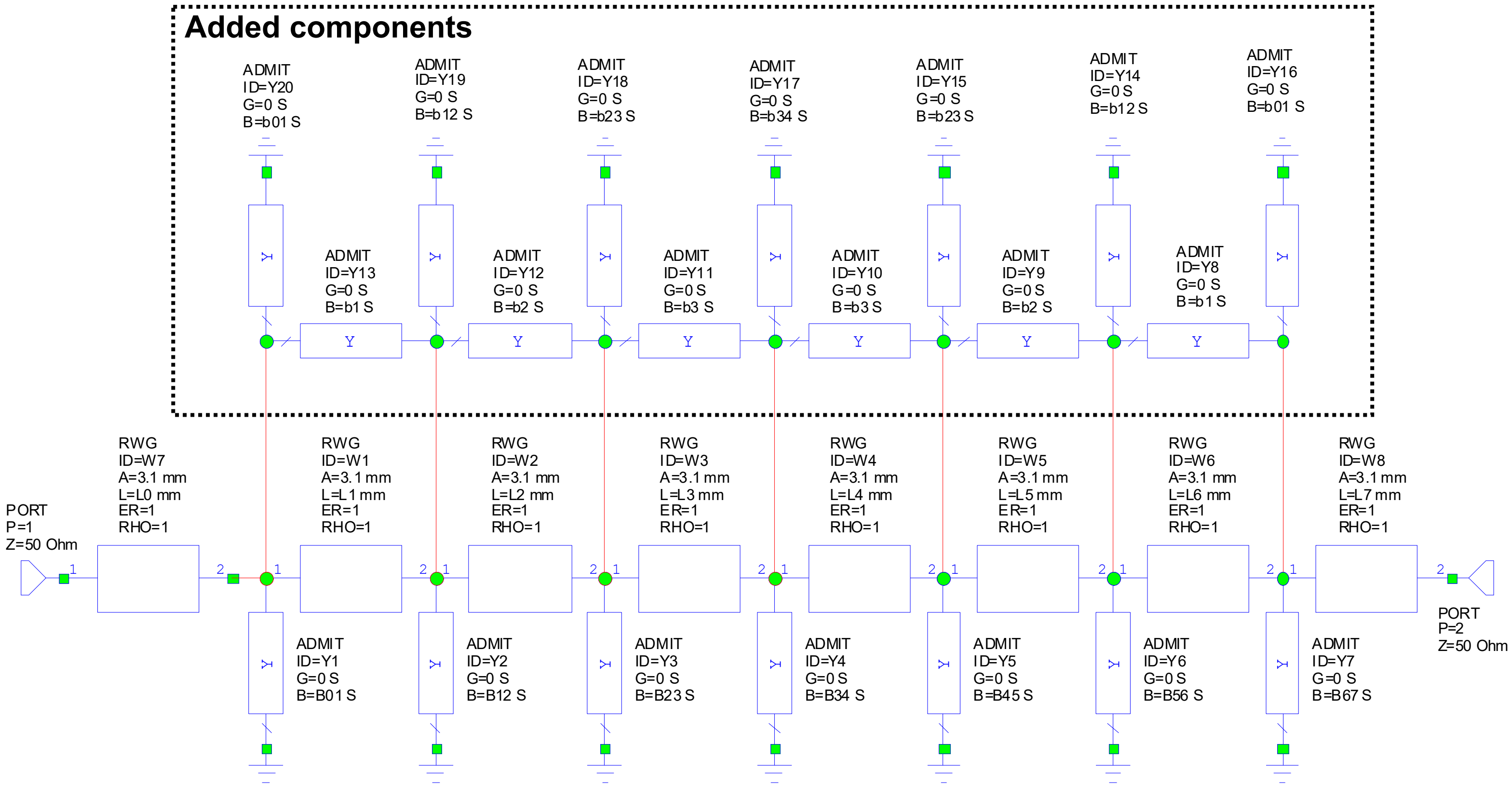
EM model

L1=2.492	W01: 1.019
L2=2.837	W12: 1.37
L3=2.907	W23: 1.457
L4=2.908	W34: 1.473
L5=2.838	W45: 1.458
L6=2.492	W56: 1.371
	W67: 1.019

Comparison of initial responses



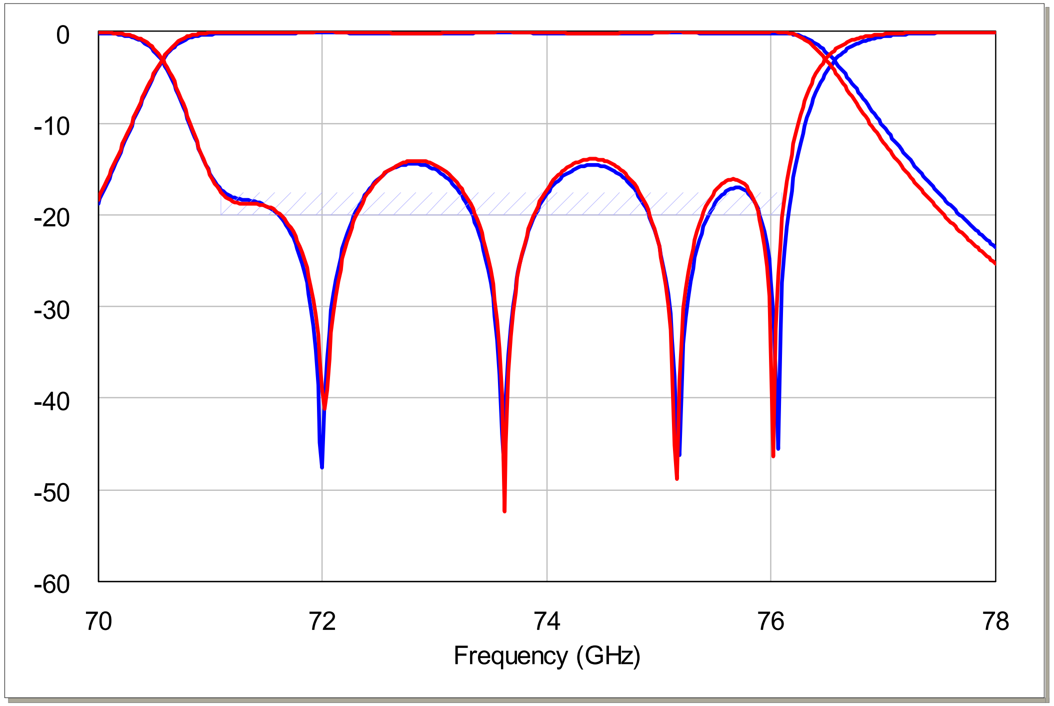
Definition of the complete coarse model



Added components (to be computed): b_{01}, b_{12}, b_{23}, b_{34}, b_1, b_2, b_3

Computation of the added parameters

Added parameters are computed through MWO optimization by imposing the match of S_{11} from circuit and EM simulations



$b1=-0.137$
$b2=-0.1513$
$b3=-0.1315$

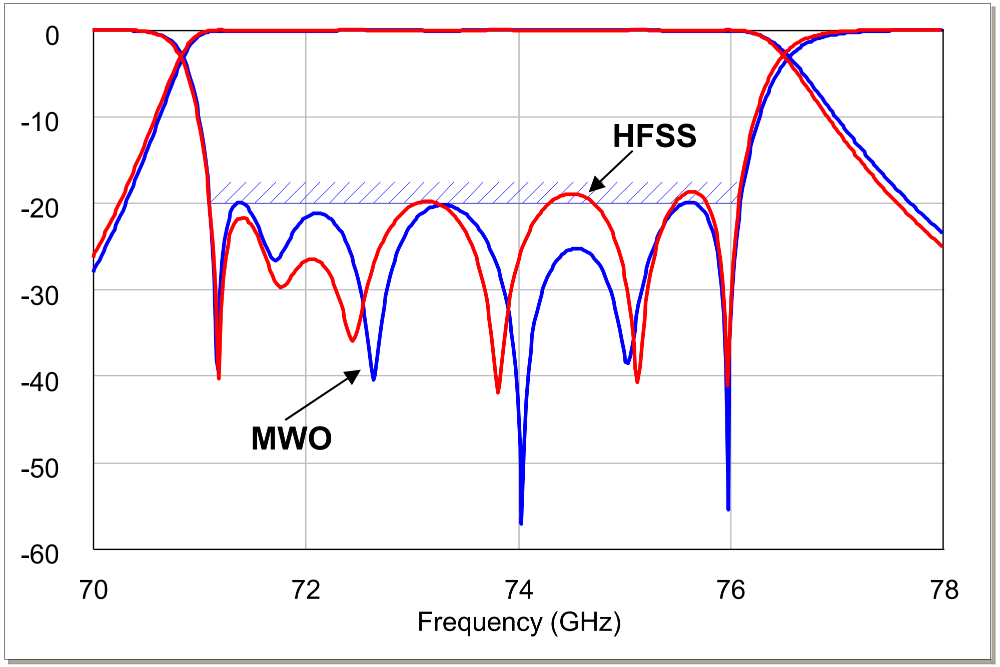
$b01=0.2211$
$b12=0.5814$
$b23=0.5817$
$b34=0.596$

New evaluation of filter dimensions

A new set of geometric dimensions (iris and waveguide lengths) can be now computed (always through optimization) by imposing the required return loss in passband (the added parameters remain unchanged).

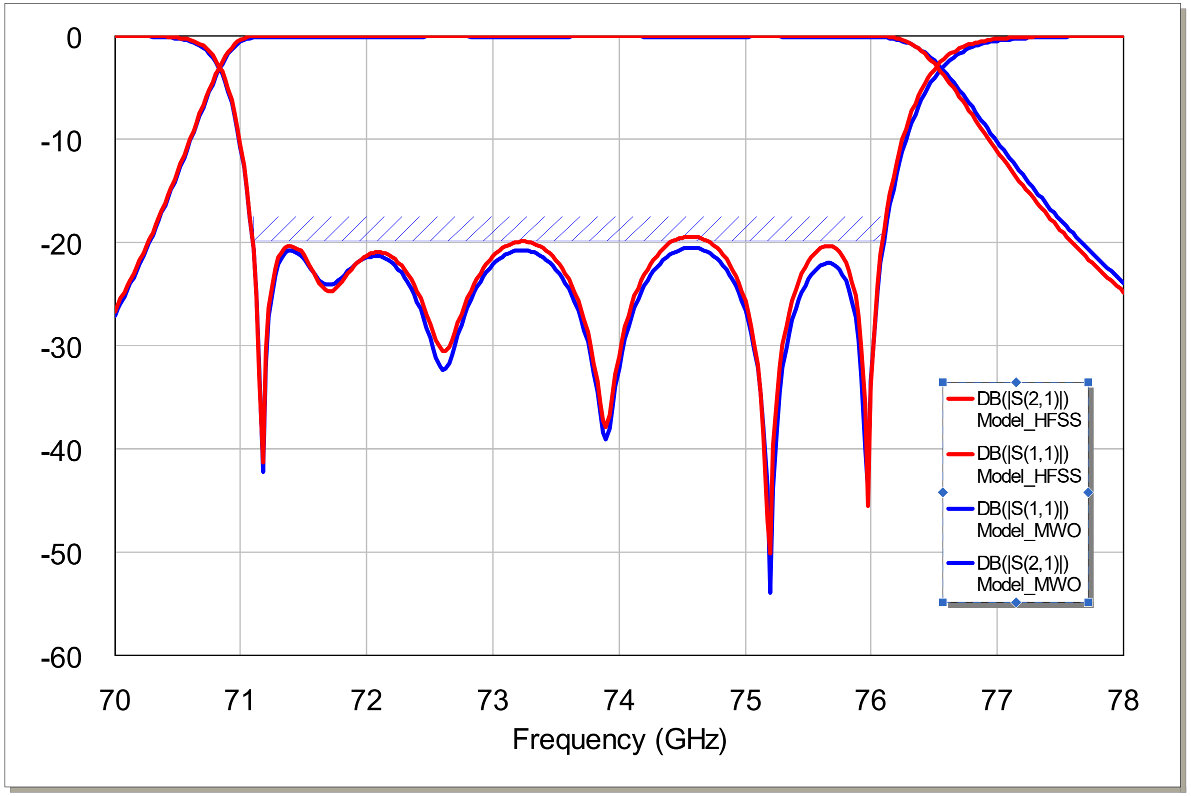
Computed dimensions

L1=2.464	W01: 1.022
L2=2.847	W12: 1.392
L3=2.914	W23: 1.473
L4=2.913	W34: 1.486
L5=2.847	W45: 1.475
L6=2.468	W56: 1.39
	W67: 1.019



A new iteration can be performed (2 circuit optimizations) for matching the computed EM response

Final result

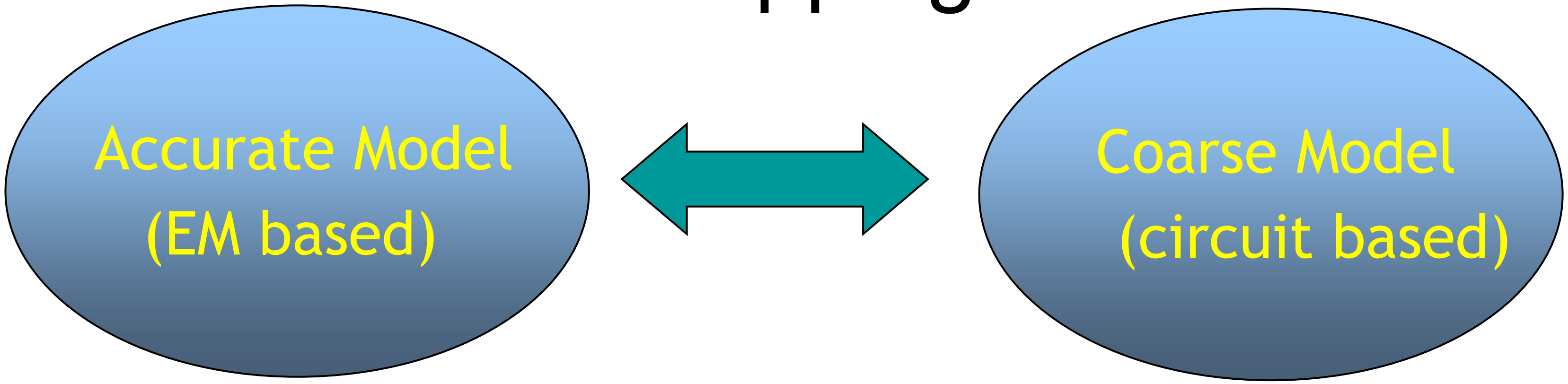


Computed dimensions

L1=2.463	W01: 1.026
L2=2.847	W12: 1.393
L3=2.919	W23: 1.476
L4=2.918	W34: 1.492
L5=2.847	W45: 1.48
L6=2.467	W56: 1.388
	W67: 1.024

This result has been obtained with only **two** EM simulations!

Another implementation of space-mapping



Both models describe the components with reference to the geometrical dimensions (***p***), but:

$$H_{EM}(f,\mathbf{p}_{EM}) \neq H_{CIR}(f,\mathbf{p}_{C}) \quad \text{with } \mathbf{p}_E=\mathbf{p}_C$$

- The space mapping looks for a suitable “mapping” of the variables assigned in the two environment so that:

$$\mathbf{p}_C = F\left(\mathbf{p}_{EM}\right) \rightarrow H_{EM}(f,\mathbf{p}_{EM}) = H_{CIR}(f,F\left(\mathbf{p}_{EM}\right))$$

- With this approach optimization is mostly performed with the circuit model reducing considerably computation time

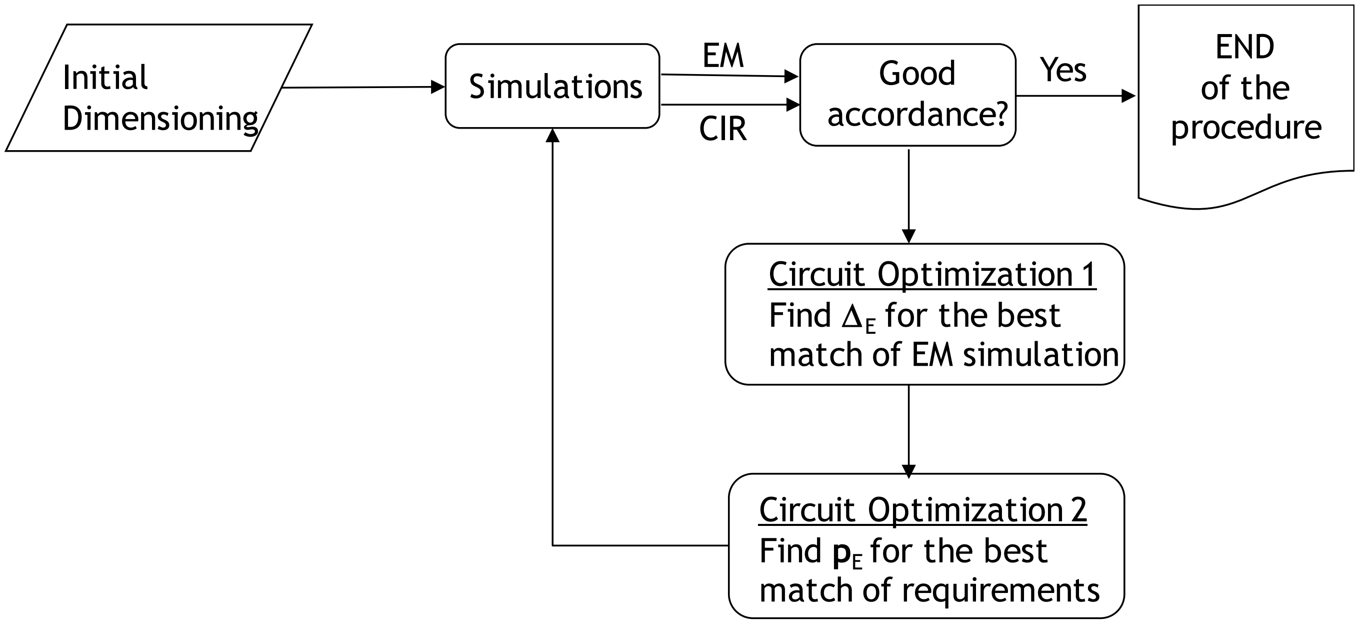
The mapping function *F*

- A simple and easy to implement mapping function is:

$$\mathbf{p}_C = \mathbf{p}_{EM} + \boldsymbol{\Delta}_E$$

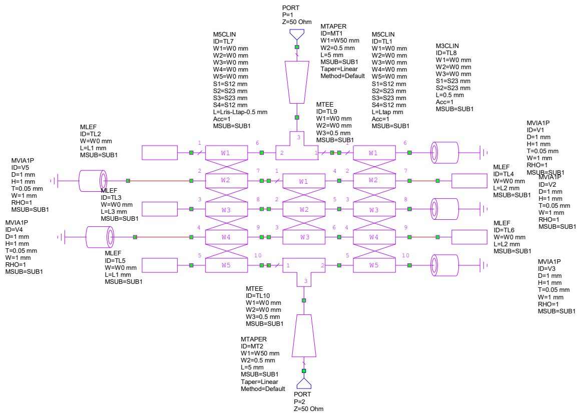
Δ_E is a vector with the same dimension of **p**

Δ_E is exploited to correct the dimension found with the circuit optimization in order to match the response computed with EM simulation:

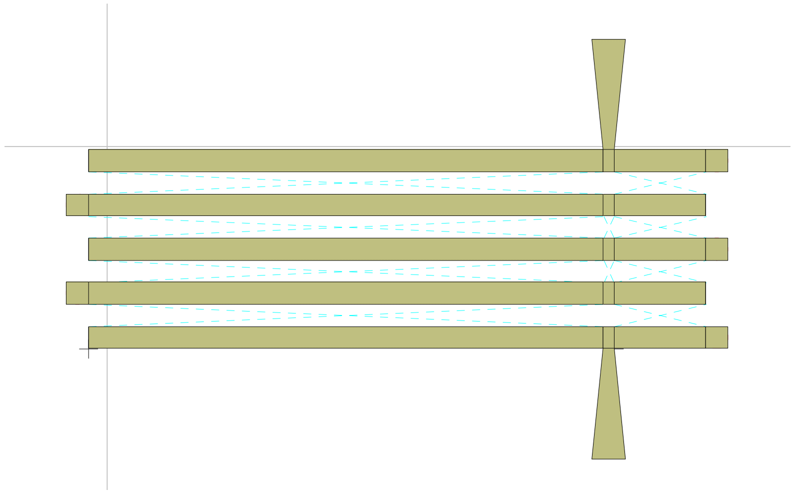


Application to the interdigital filter design

- Passband: 1800-2000 MHz, Return Loss: 18 dB
- Filter order: 5
- Previously dimensioned with the circuit models of MWoffice



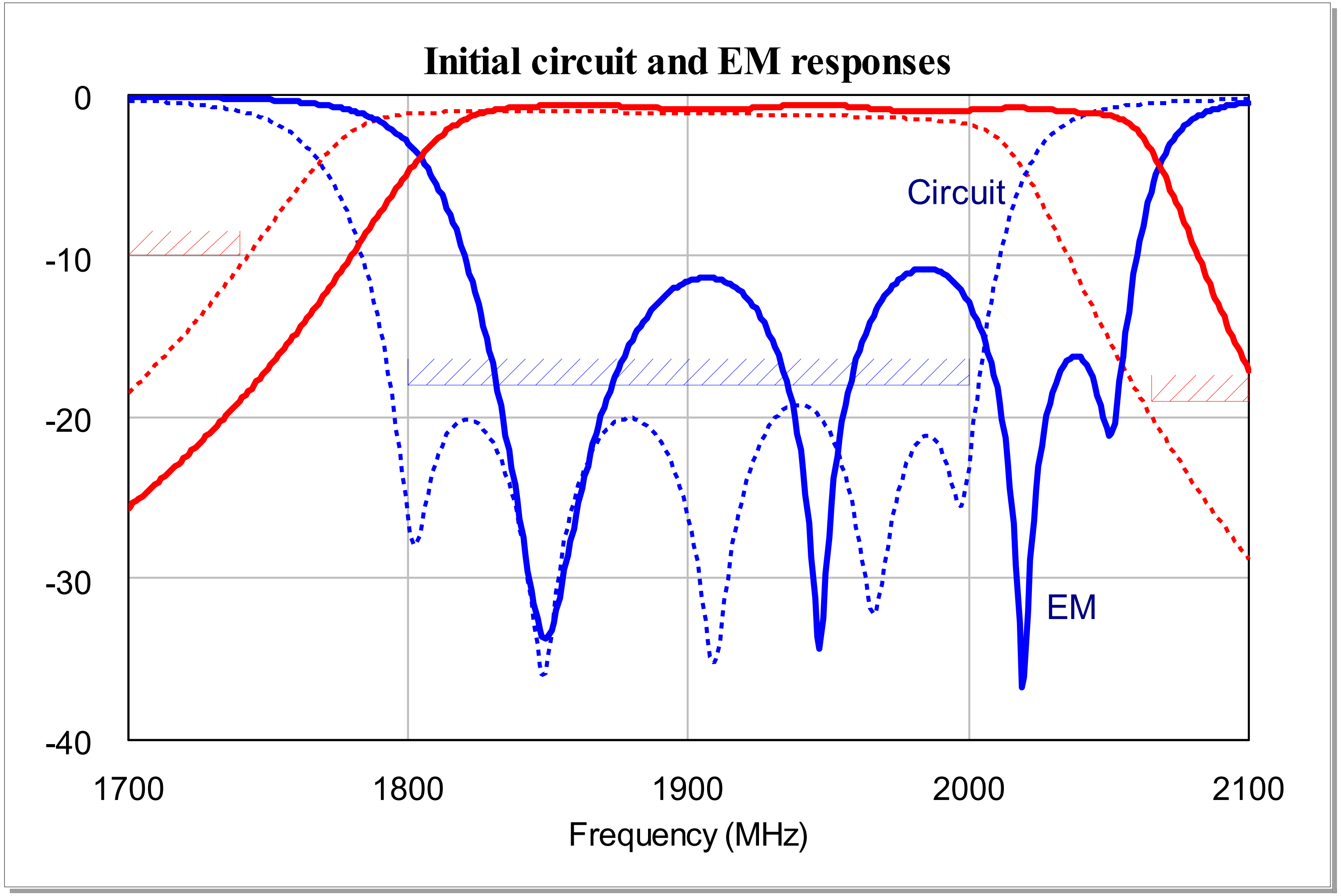
Circuit model



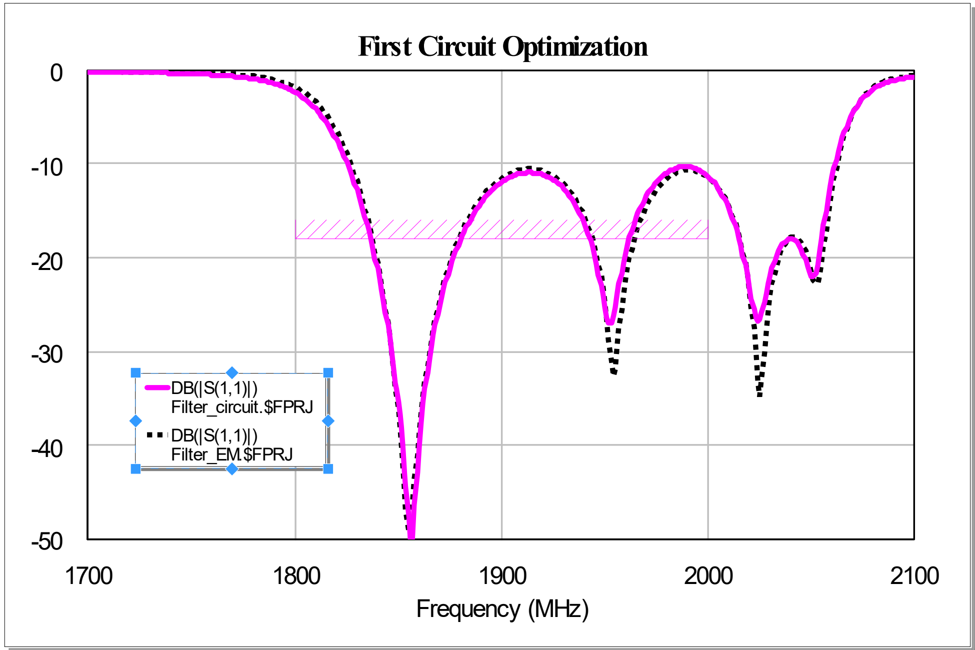
Physical Structure (Axiem EM simulator)

- <u>Variables to be modified for improving EM response</u>: Lris, L1,L2,L3,S12,S23, Ltap

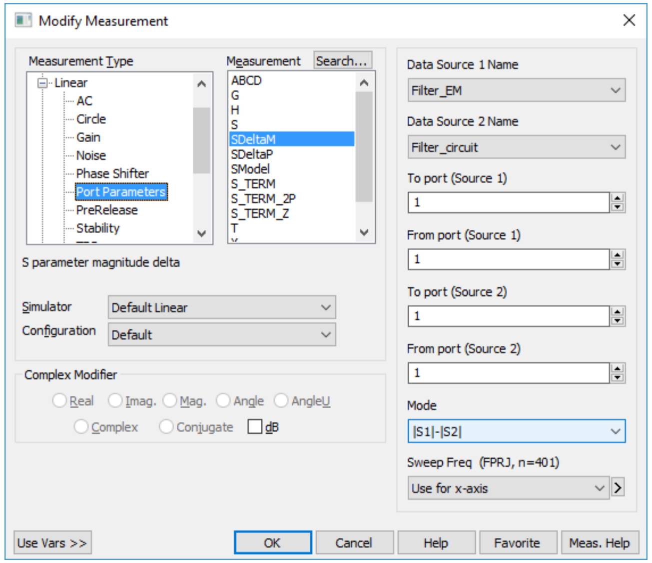
Initial filter responses



- First circuit optimization for finding the Δ_E vector:



The match of EM and Circuit response is evaluated on |S11| response. The measurement used in optimization is <u>SDeltaM</u>:



Vector p_{EM}:

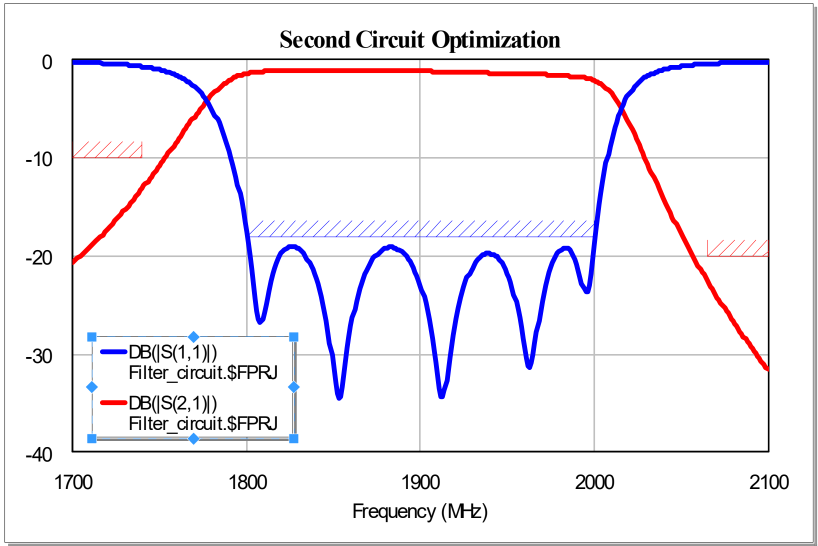
Lris_0=27
L1_0=1.96309799229905
L2_0=0.912383473918164
L3_0=0.90200714932847
S12_0=1.08977613149629
S23_0=1.42956231363555
Ltap_0=4.1934742145235

Vector Δ_E :

Delta0=-0.6182
Delta1=0.0666232607285427
Delta2=-0.019159054188831
Delta3=-0.0293554878937105
Delta4=-0.00857177118752791
Delta5=0.0168900174282014
Delta6=-0.515241012963923

Note: before starting optimization is convenient to adjust Delta0 (Lris) in order to center the band of EM response

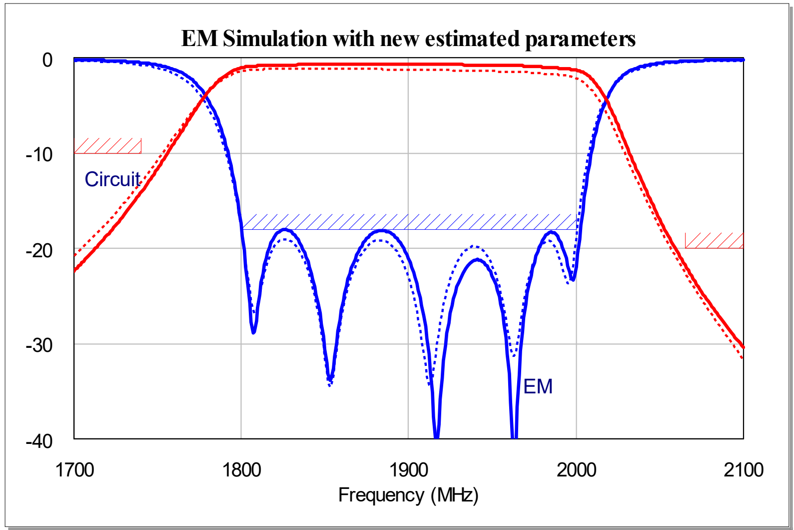
- Second circuit optimization (search of $\mathbf{p}_{EM}$ vector for the best fit of requirements):



Vector $\mathbf{p}_{EM}$:

Lris_0=27.66
L1_0=1.888
L2_0=0.9445
L3_0=0.9209
S12_0=1.138
S23_0=1.445
Ltap_0=4.611

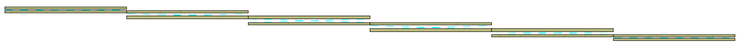
- EM Simulation with the new $\mathbf{p}_{EM}$ vector:

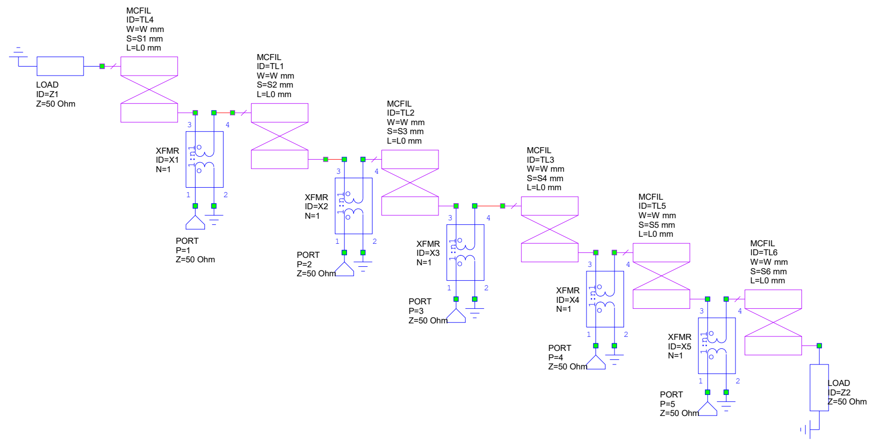


Only 2 EM simulations required!

Other filters type suitable for the extracted parameters design approach

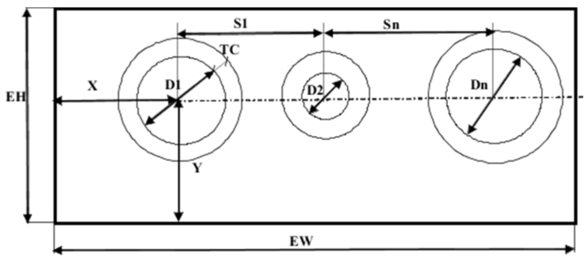
- Parallel coupled line (microstrip)





Parameters extracted from the multiport Z matrix

- Comb (coaxial)



RCCOAX element